Investigation of the Resistive Behavior of a Type-II Superconductor Near the Upper Critical Field Strength

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The volt-ampere characteristics of recrystallized Nb-80% Zr foils are measured near the critical magnetic field strength. A peak effect occurs in the immediate vicinity of H_{c2} on the $I_c(H)$ curves. The resistive transition in the peak region is strongly smeared out and this results in a considerable increase of the current corresponding to the given electric field. Possible causes of this behavior are discussed. It is found that in a certain range of magnetic field strengths there may arise on the V(I) curves a hysteresis which is connected with a definite initial state of the vortex-line lattice. The $H_{c2}(T)$ and $H_{c3}(T)$ dependences are determined in the temperature range from 4.2°K to 8.1°K. The value obtained for $H_{c2}^{e}(0)$ is compared with that predicted by the GLAG and Maki and Werthamer theories. On variation of temperature the ratio H_{c3}^{e}/H_{c2}^{e} is found to increase considerably near T_c; this fact is in good agreement with the fluctuation theory.

ONE of the interesting fields of research on type-II superconductors is the interval of magnetic fields close to the upper critical field. The present paper is devoted to an investigation of the peak effect observed on the $I_c(H)$ curves. One can assume that there exist at least two phenomena of this kind, which differ greatly in nature. In the first case, the peak effect arises only near the upper critical field and can be observed even in single-phase superconductors.[1–4] For the second case to occur, the superconductor must contain particles whose properties vary with the field in such a way that their effectiveness as pinning centers increases with increasing field.[5–7] The peak effect can be observed in this case also far from $H_{c2}(T)$. Of course, intermediate or mixed cases are also possible.

There is still no meeting of minds concerning the conditions and causes of the peak effect of the first type, the results of an investigation of which are given by us here. Measurements in the immediate vicinity of H_{c2} have made it possible to obtain the $H_{c2}(T)$ dependence and to estimate the absolute value of $H_{c2}(0)$ and to compare it with the theoretical calculations.[8–12] In addition, we have attempted to determine the limiting superconductivity field, which we arbitrarily called H_{c3}^{e}, from the current-voltage characteristics in fields somewhat above H_{c2} and from the dependence of the sample resistance on the field at a small constant value of the measuring current. The experimentally obtained temperature dependence $H_{c3}^{e}(T)$ is compared first with the theory of surface or nucleation superconductivity in the presence of a paramagnetic effect,[13] and, second, with the theory that takes fluctuation phenomena into account.[14,15]

EXPERIMENTAL PART

Samples made of Nb-80% Zr alloy in the form of flat plates measuring 0.1 × 1.6 × 50 mm were subjected, after mechanical working, to recrystallization annealing at 1000°C for one hour in a vacuum of $\sim 10^{-6}$ mm Hg followed by rapid cooling.[1)] X-ray diffraction revealed no considerable decay of the solid solution. The grains, whose axes were approximately the same, measured 5–20 μ. The peak effect was measured in a magnetic field perpendicular to the flat surface of the samples, at temperatures from 1.5 to 8.1°K.

To prevent overheating the peripheral sections, which are situated in a decreasing magnetic field, during the course of measurements in the region of the peak $I_c(H)$, two strips of an alloy with a higher critical current were clamped tightly against the sample, over its entire length (with the exception of a central part 4.5 mm long). The distance between the main potential contacts at the center of the sample was 3.5 mm. Control contacts were placed on the side of each main contact at a distance 3 mm.

The current-voltage characteristics were plotted with the aid of a high-sensitivity photoelectronic amplifier, and a special superconducting amplifier was used in the voltage range 10^{-9}– 10^{-6} V (measurements with this amplifier were impossible in fields stronger than 60 kOe, owing to the large stray magnetic field of the superconducting solenoid).

The values of H_{c2}^{e} and H_{c3}^{e} at different temperatures were determined from the resistance characteristics of the superconducting transition in an external magnetic field parallel or perpendicular to the plane of the plate. The current in the sample was always perpendicular to the magnetic field. The measurements were performed in the temperature interval from 4.2 to 8.1°K. Figure 1 shows typical R(H) plots in parallel and per-

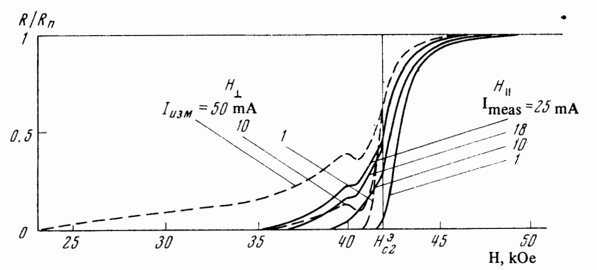

FIG. 1. R(H) plot for a field perpendicular to the sample plane (dashed lines) and parallel to it (continuous lines) at different values of the measuring current; T = 6.2°K.

[1)]The heat treatment of the samples and their metal-physics investigations were carried out under the leadership of L. A. Elesin and G. P. Saenko. Detailed results will be published elsewhere.

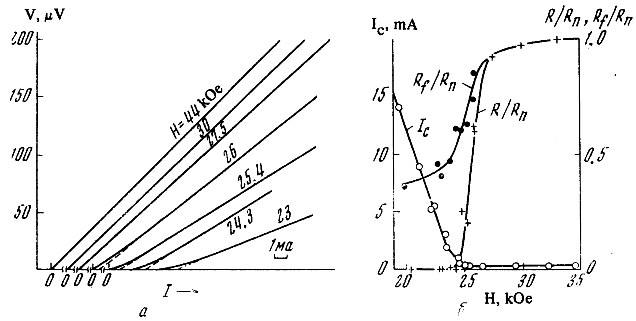

FIG. 2. Plots of V(I) at H = const (a) and of R/R_n, R_f/R_n and I_c (V = 2 μV) against H at T = 7.0°K and H parallel to the plane of the sample (b); in the case b, R was defined by $R = (V/I)_{I = 1mA}$.

pendicular fields at T = const for different values of the measuring current.

As seen from the figure, the value of H^e_{c2} is assumed to correspond to the characteristic kink on the curves, above which the R(H) coincide for different measuring currents. Since most measurements were performed at a current of 1 mA through the sample (j = 0.6 A/cm^2), we assume on the basis of the foregoing that H^e_{c2} in the case of $H_\perp$ is the field corresponding to $R/R_n \approx 0.6$, and in the case of $H_{\parallel}$ it corresponds to a ratio $R/R_n \approx 0.05$ (R_n is the resistance of the sample in the normal state). The values of H^e_{c2} obtained in this manner fall with good accuracy on a single curve (Fig. 3).

H^e_{c3} was assumed to be the field in which $R/R_n = 0.98$. In addition, H^e_{c3} was determined more accurately from the current-voltage characteristics of the sample. As seen from Fig. 2b, when $R/R_n \gtrsim 0.9$ the quantities R_f/R_n and R/R_n ($R_f = \partial V/\partial I$ is the differential resistance) are equal, corresponding in the V(I) plot (Fig. 2a) to a straight line drawn from the origin. By plotting such current-voltage characteristics on an x-y recorder at different fields H = const in a wide range of I and V, it is possible to determine with high accuracy the change of their slope and consequently also H^e_{c3} for any R/R_n. In particular, Fig. 3 shows the values of H^e_{c3} corresponding to $R/R_n \geq 0.995$.

Notice should be taken of the change in the form of the current-voltage characteristics when the magnetic field is decreased (Fig. 2a). The strictly linear V(I) characteristics referred to above experience a kink at a certain value of the field and form two linear sections, the slopes of which differ noticeably from each other (for example, in the case T = 7°K at H ≈ 26 kOe, see Fig. 2). Starting with this instant we have $R_f \neq R$. Further decrease of the field leads to a gradual curving of the first section, which initially starts from zero, and then, in still stronger fields, the V(I) curves shift to the right. When the initial sections of the V(I) curves were measured with a more sensitive instrument (accuracy to 0.01 μV), it was observed that the initial linear V(I) dependence holds even if the critical current differs noticeably from zero. The usual exponential V(I) dependence appears only at a sufficiently large distance from H_{c2}.

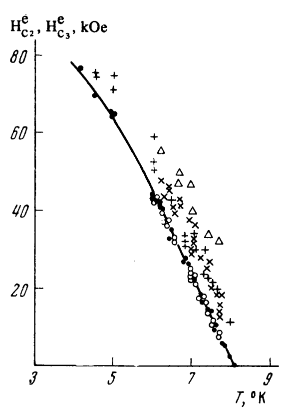

FIG. 3. The temperature dependence of $H_{c2}{}^e$ and $H_{c3}{}^e \equiv H|_{R/R_n = 0.98}$ in perpendicular and parallel fields: ●) $H_{c2}{}^e$ at $H_\perp$, ○) $H_{c2}{}^e$ at $H_\parallel$, +) $H_{c3}{}^e$ at $H_\perp$, ×) $H_{c3}{}^e$ at $H_\parallel$. The triangles show the values of $H_{c3}{}^e$ determined from the V(I) characteristics of the sample and corresponding to a field for which $V/I \equiv R_n$, i.e., $R/R_n \geqslant 0.995$.

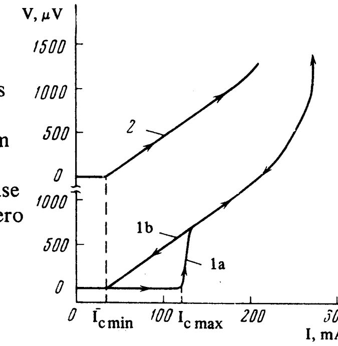

FIG. 4. Current-voltage curves plotted for a sample in different initial states: 1) after cooling from $T > T_c$ in a given magnetic field, 2) after a preliminary slow decrease of the current from 390 mA to zero (T = 4.2°K, H = 63 kOe).

MEASUREMENT RESULTS

1. Hysteresis on Current-voltage Characteristics

In the investigation of the V(I) dependence of a given series of samples, an interesting singularity was observed. Starting with a certain field value typical of each temperature (for example, with 52 kOe for 1.8°K), and up to the field corresponding to the peak effect (H_{peak}), we can obtain current-voltage characteristics of two different types, depending on the initial state of the sample (Fig. 4). If the sample in the constant magnetic field was cooled from $T > T_c$ to a specified temperature, then the result was a V(I) curve analogous to curve 1a. On the other hand, if the sample, was transformed from the resistive state to the superconducting state by decreasing the current at a rate ≲ 1 A/sec, then when the current was subsequently increased again, a current-voltage characteristic of the usual type was obtained (curve 2). The sample was superheated above T_c by passing a sufficiently strong current through it. By varying the rate of decrease of this current and the initial point on the curve of type 1a, it was possible to obtain, after turning on the current again, a set of arbitrary curves intermediate between 1a and 1b. Some of them had $I_c \approx I_{c.min}$ with a subsequent slight growth of the voltage up to $I_c \sim I_{c.max}$. It is important to emphasize that at any point of the intermediate curves (with the exception of their steepest sections) the voltage $0 < V < V_{max}$ remained stationary at a given current through the sample (here $V_{max}(I)$ corresponds to curve 1b). The significance of this fact, and also the possible causes of the hysteresis, will be discussed later on.

2. Character of the Transition in the Vicinity of the Peak Effect

We present below results pertaining mainly to that initial state of the sample in which the critical current

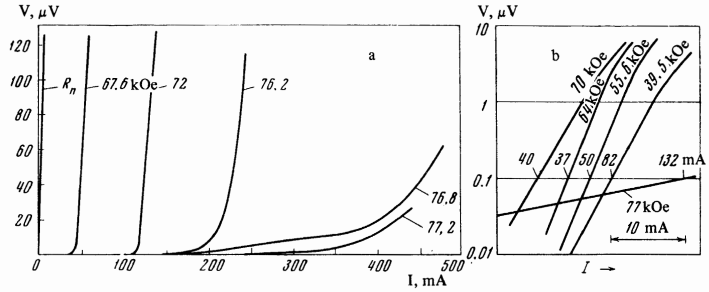

FIG. 5. Typical form of current-voltage characteristics in magnetic fields corresponding to the "valley" and the peak of the $I_c(H)$ curves (T = 4.2°K): a) large V, linear scale; b) small V, semilogarithmic scale. The number with the arrow denotes, for the corresponding curve, the current (in mA) at which V = 0.1 μV.

is minimal (i.e., the current-voltage characteristics have the usual form). Figure 5 shows, in linear and semilogarithmic scales, typical transition curves. First, both in the region of the peak effect and in weaker magnetic fields, the V(I) dependence at low voltages ($\lesssim 3$ μV) is exponential. Second, when H_{peak} is approached, the transition becomes more and more smeared out. This is particularly evident in Fig. 6, which shows a plot of the slope of the straight line log V = f(I) against the magnetic field. $\partial(\log V)/\partial I$ first increases, and then decreases to not more than one-tenth of the maximum value in the region of the peak. Third, the value of I_p, i.e., of the current obtained by extrapolating the linear part of the V(I) curve to V = 0, increases significantly in the region of the peak. This means that the $I_p(H)$ curve also has a peak, in full agreement with the data of [4]

3. $I_c(H)$ and R(H) Plots at Different Temperatures

Figure 6 shows plots of $I_c(H)$, i.e., the current that must be drawn through the sample to obtain a given value of the electric field E. At 4.2°K, the hysteresis on the V(I) curves is observed in the range of fields from 45 kOe to H_{peak}. For simplicity, the figure shows mainly the $I_{c.min}(H)$ curves, and the $I_{c.max}(H)$ curve is shown only for E = 10^{-7} V/cm. For other values of the electric field, the $I_{c.max}(H)$ curves deviate from the $I_{c.min}(H)$ curves also in the 45 kOe region, and converge in the peak-effect region. For E equal to 10^{-8} and 10^{-9} V/cm, above 60 kOe, the figure shows dashed curves obtained by extrapolating the linear log V = f(I) dependence into the region of small voltages.

In some cases a small satellite peak is observed ahead of the main peak on the $I_c(H)$ curve. The satellite position was shifted by 1.5 kOe towards larger magnetic fields after treating the surface sample slightly with very fine (micron) emery paper. This left the position of the main peak unchanged, but the critical current in medium fields increased by 1.7 times.

The main peak on the $I_c(H)$ curves corresponds to a minimum on the R(H) ay I = const curves. It is seen from Fig. 7, which shows plots of R/R_n against H for different temperatures, that the minimum practically disappears at $T/T_c \sim 0.87$ (this picture depends little on the variation of the measurement current in a wide range).

The experimentally determined value of H_{c2} (Figs. 1 and 3) turned out to be somewhat larger than H_{min} on the R(H) curves, and accordingly, larger than H_{peak} on the $I_c(H)$ curves. In the region $t = T/T_c = 0.5$–0.8, we have $H_{peak}(T)/H_{c2}(T) \approx 0.97$. This is much higher than the ratio 0.84 obtained for cold-deformed Nb-5 at.% Ti in [3] at t = 0.5–0.8. We note also that the characteristic minimum on the R(H) curves is also observed in the case of a field parallel to the flat surface of the sample.

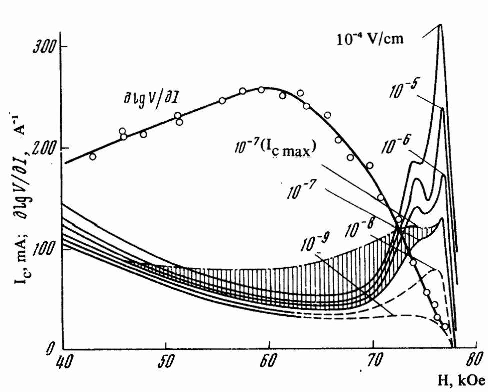

FIG. 6. Plots of I_c(E = const) and $\partial(\log V)/\partial I$ against the magnetic field (T = 4.2°K). The region where hysteresis of V(I) is observed is shown shaded.

DISCUSSION OF RESULTS

1. Hysteresis on Current-voltage Characteristics

Since the critical current can increase by several times after cooling of the sample from $T > T_c$ in a given magnetic field, it is reasonable to assume that this is a consequence of a vortex-filament (fluxoid) configuration such that the bond of each of them with the pinning centers is maximal. It is quite probable that the indicated configuration is metastable. In any

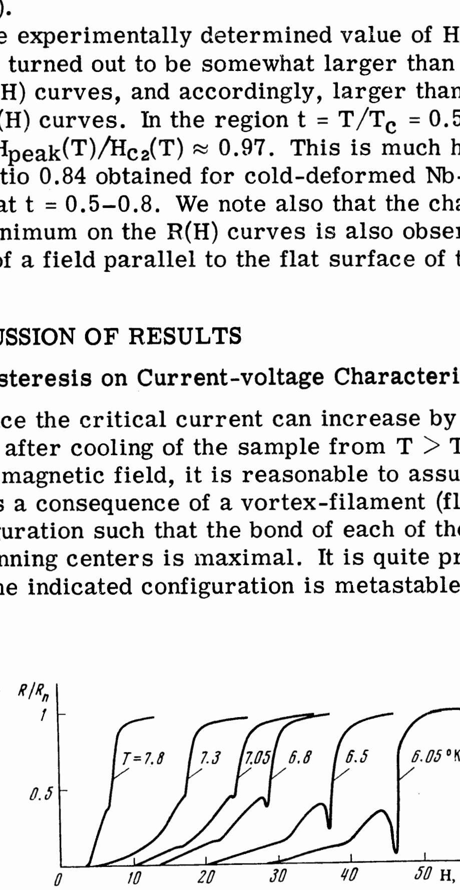

FIG. 7. Dependence of R/R_n on the magnetic field at different temperatures (measuring current 25 mA).

case, after a $V_{max}(I)$ dependence is reached under the influence of the increasing current (i.e., curve 1b of Fig. 4) and the current has been reduced to zero, a different vortex lattice configuration is obtained and corresponds to the minimum critical current.

In weak magnetic fields, the current-voltage characteristics have the usual form, regardless of the initial state. This is more readily connected with the fact that bundles of fluxoids can form here,[16,17] and as a result the interaction of the fluxoids with the pinning centers averages out, and the resultant configuration is always the same. That the number of fluxoids in the bundle decreases with increasing magnetic field is indicated by the results of [18]. A similar hysteresis was observed on the current-voltage characteristics in [19] in an investigation of the dynamic intermediate state of type I superconductors, and also in [20], where Nb-8 at.% Ti samples containing ω-phase particles were investigated.

2. Peak Effect Near the Upper Critical Field

We discuss first the conditions for experimental observation, where there is some unambiguity in this question. Thus, in [21] it is stated that the peak effect was observed at I_c ($E = 4 \times 10^{-7}$ V/cm), but not at I_c (4×10^{-4} V/cm) in the same sample. The paper presents current-voltage characteristics "with steps," and indicates that prior conditioning was used in the measurement of the critical current. We assume that such behavior is a consequence of the hysteresis phenomena under conditions of an uncontrollable initial state. Apparently, I_c ($E = 4 \times 10^{-4}$ V/cm) should actually be set in correspondence with $I_{c.max}$ (in terms of our paper), and the absence or presence of a peak on the $I_{c.max}(H)$ curves can depend in general on causes other than the peak on $I_{c.min}(H)$.

It is universally recognized that the peak effect near the upper critical magnetic field becomes noticeable only when sufficiently effective pinning centers are present in the sample.[22-24] On the other hand, when the temperature changes, the ratio $H_{peak}(T)/H_{c2}(T)$ remains approximately constant,[3,25] as is also confirmed by our results. This suggests that the occurrence of the peak effect is connected with a definite change in the properties of the vortex lattice, which becomes particularly noticeable near H_{c2}.

In [17] there is a brief remark that on approaching H_{c2} the fluxoid lattice becomes more rigid in the sense that the vortices cannot move independently relative to one another. This should lead to a slowing down of the motion of the vortices and consequently to a peak effect. Pippard[26] has recently proposed a model according to which near H_{c2} the rigidity[2)] of the vortex lattice decreases in proportion to $(H_{c2} - H)^2$, and the pinning force is proportional to $H_{c2} - H$. As a result of this there can arise, with a higher probability than in weaker fields, a vortex configuration corresponding to the minimum energy, and this leads to an increase of the critical current. The character of the current-voltage characteristics is not touched upon at all by Pippard. However, as seen from our investigation, the V(I) curve changes quite strongly near the peak, and therefore a complete theory of the phenomenon should consider this question, too.

We assume that the growth of $I_p(H)$ and the "smearing" of the current-voltage characteristic in the region of H_{peak} are due to the following factors. As is well known, in the presence of pinning, the linear section of V(I) is practically parallel to the current-voltage characteristic of a defect-free superconductor, but does not necessarily coincide with it[27] (i.e., the continuation of the linear section does not pass through the origin). This indicates the presence of an additional friction force exerted by the pinning centers on the moving fluxoids ($F_{fr.p}$):

$$F_{\mathrm{fr\ p}} = j\varphi_0 / c - \eta v_L,$$

where ηv_L is the friction force in the defect-free superconductor. If the current-voltage characteristics were straight lines, starting with V = 0, then we could state that $F_{fr.p}$ does not depend on the velocity of the fluxoids and is exactly equal to the maximum static pinning force $j_c \varphi_0/c$ (we shall denote this limiting friction force by $F_{fr.p}^{lim}$). Experiment shows, however, that the current-voltage characteristics have initial nonlinear sections, which become particularly appreciable in the region of H_{peak}. It is natural to assume that in such a section there is also a friction force exerted by the pinning centers, and this force should be regarded here as dependent on the vortex velocity. Obviously, near H_{c2} there is an increase of $F_{fr.p}^{lim}$, since experiment shows an appreciable growth of $I_p(H)$. In our case, in the region of H_{peak}, there was practically no increase of the critical current corresponding to the smallest electric fields, i.e., the bulk pinning force changed insignificantly. As a result, the current-voltage characteristics turned out to be strongly smeared out. The growth of the additional friction force and hence the occurrence of the peak effect are apparently connected with the decrease of the elasticity of the lattice.[28] Such a decrease, in our opinion, is indicated also by the vanishing of the hysteresis on the V(I) curve at $H = H_{peak}$.

Finally, let us dwell briefly on the results of the measurement of the peak effect at increased temperatures. As seen from Fig. 7, when T_c is approached the minimum on the R(H) curves and, consequently, the peak on $I_c(H)$ decrease gradually and, starting with a certain temperature, the two disappear completely. This can be the consequence of the growth of the correlation parameter $\xi(T)$[23,24] (at the temperatures at which the peak vanishes, $\xi(T)$ is 2–3 times larger than at low temperatures). It is not excluded, however, that the properties of the vortex lattice change near T_c in such a way that there is no longer a noticeable increase of the additional friction force as $H \to H_{c2}(T)$.

3. Temperature Dependence of H_{c2}^e and H_{c3}^e

As follows from Fig. 3, which shows the temperature dependence of H_{c2}^e, the experimental points near $T = T_c$ fit well a straight line, from which we get

$$(dH_{c2}^e / dT)_{T=T_c} = 22 \text{ kOe} / {}^\circ\text{K}.$$

For comparison with the theory, we determined the

2)By "decrease of rigidity" is meant here a change of the elastic properties such that the energy necessary to realign the lattice (for example from triangular to rectangular) is decreased.

value of $H^e_{c2}(0)$. According to the results of [29], the relation $H_{c2}(t) = H_{c2}(0)(1 - t^2)$ is well satisfied for the alloy Nb-80% Zr, so that by extrapolating the linear $H^e_{c2}(t^2)$ dependence to t = 0 we obtain

$$H_{c2}{}^{э}(0) = 104 \text{ kOe}.$$

The experimental value of $H^e_{c2}(0)$, averaged over several samples, is compared with the theory.

1. From the GLAG theory[8] for dirty superconductors ($l \ll \xi_0$) we have at T = 0

$$H_{c2}(0) = 2.6 \cdot 10^4 \gamma T_c \rho_n, \qquad (1)$$

where γ [erg/cm^{3}deg^2] is the coefficient of the linear term of the electronic specific heat, T_c[°K] is the critical temperature of the superconducting transition, and ρ_n[Ω-cm] is the resistivity in the normal state. Substitution of the experimental values $T_c = 8.1$°K, $\rho_n = 86.2 \times 10^{-6}$ Ω-cm and $\gamma = 0.93 \times 10^4$ erg/cm^{3}deg^2 (obtained by extrapolation of the data of [30]) yields

$$H_{c2}(0) = 169 \text{ kOe}.$$

2. According to the Maki formula,[9] in which account is taken of the Pauli spin paramagnetism,

$$H_{c2}{}^*(0) = H_{c2}(0) / (1 + \alpha^2)^{1/2} \quad (T = 0). \qquad (2)$$

Here $\alpha = \sqrt{2}\, H_{c2}(0)/H_p(0)$, $H_p(0) = 18\,400\, T_c$. Independently of the method of calculating $H_{c2}(0)$ (using formula (1) or (3), see below), we obtained

$$H_{c2}{}^* = 79 \text{ kOe}.$$

3. The theory of Werthamer et al.[10] takes into account both the spin paramagnetism of the electrons and the spin-orbit scattering. For the case $t \equiv T/T_c = 0$, the dependence of the normalized critical field

$$h^*(0) = \frac{H^{**}_{c2}(0)}{(-dH^{**}_{c2}(t)/dt)_{t=1}}$$

on the parameters α and $\lambda_{so} = \hbar/3\pi k T_c \tau_{so}$ was obtained in [11]. Here $\tau_{so} = l_{so}/v_F$, α is the Maki parameter, l_{so} is the mean free path of the electrons for spin-orbit scattering (it is assumed that $l_{so} \gg l$), v_F is the electron velocity of the Fermi surface, and H^{**}_{c2} is the upper critical field of this theory.

Such a normalization was introduced by Werthamer [12] to compare the theoretically calculated h* with experiment. In this normalization, in particular, we obtain in the limiting case $\alpha = 0$ and $l \ll \xi_0$, the following expression for the critical field after GLAG:

$$H_{c2}(0) = 0.693\,(dH_{c2}{}^{э}/dt)_{t=1}. \qquad (3)$$

It should be noted, however, that the quantity $H_{c2}(0)$, determined from formulas (1) and (3), is not always unique, as follows, for example, from [31], in which are given experimental values of $(dH_{c2}/dt)_{t=1}$, T_c, ρ_n, and γ. In our case $H_{c2}(0) = 169$ kOe in accordance with formula (1) and 123 kOe in accordance with (3). The parameters α and λ_{so} of the theory can be determined from the electronic constants of the normal state:

$$\alpha = 2{,}35\, \rho_n \gamma = 1{,}9, \qquad (4)$$

if $H_{c2}(0)$ is determined from (1) and

$$\alpha = 5.33 \cdot 10^{-5} (dH_{c2}{}^{э}/dT)_{T=T_c} = 1{,}2 \qquad (5)$$

if $H_{c2}(0)$ is determined from (3); finally,

$$\lambda_{so} = 2{,}97 \cdot 10^{-13} / \rho_n \gamma T_c l^2 = 8.45 \qquad (6)$$

assuming that $l_{so} = 2l$, where $l = 1.27 \times 10^4 [\rho_n N^{2/3}(S/S_F)]^{-1}$, N is the number of valence electrons per cm^3, and $S/S_F = 0.6$.[11]

The experimental value h*(0) = 0.585 is compared with the theoretical h*(0) = f (α, λ) obtained from the calculated values of α and λ_{so}. If α is determined from (4), then h*(0) = 0.62, and if α is calculated from (5), then h*(0) = 0.67.

It is seen from the foregoing that the experimental value of the upper critical field agrees best with the theory that takes into account, in addition to spin paramagnetism, also the influence of the spin-orbit interaction.[10-12] This is clearly illustrated by the following data, which give the deviation of $H^e_{c2}(0)$ in accord with (2) from the value calculated in the corresponding theory:

Theory	Deviation
GLAG [8]:	53%–in accord with (1), 18%–in accord with (3)
Maki [9]	24%–in accord with (2)
Werthamer et al. [10-12]:	6%–α in accord with (4), 14%–α in accord with (5)

It should be recognized that λ_{so} was calculated under a number of assumptions, and that the coefficient γ which enters in the definition of α and λ_{so} was obtained by extrapolation.

From the experimental data we obtained the temperature dependence of the ratio $H_{c3}(T)/H^e_{c2}(T)$. As follows from Fig. 8, which shows a comparison with the theory of St. James, which describes the temperature behavior of $H^*_{c3}(T)/H^*_{c2}(T)$ for different values of α,[13] in the region t = 0.6–0.8 the experimental points lie somewhat lower than the theoretical curve, whereas near T_c an appreciable growth of H^e_{c3}/H^e_{c2} is observed in comparison with the limiting theoretical value 1.69.

On the other hand, according to Maki[14], as $T \to T_c$, an appreciable role is taken by fluctuation phenomena in type-II superconductors with a minimal electron mean

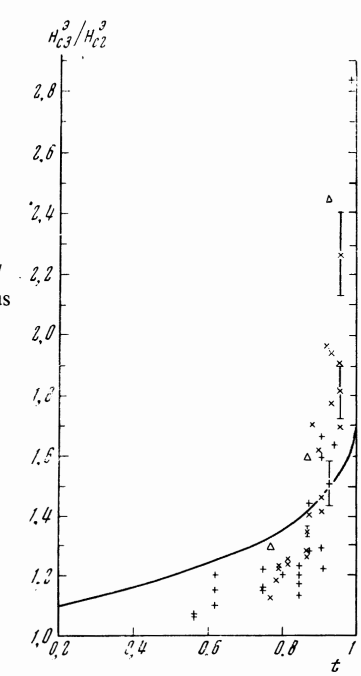

FIG. 8. Dependence of $H_{c3}{}^e/H_{c2}{}^e$ on t = T/T$_c$. The continuous curve was obtained theoretically by St. James [13] for $\alpha^2 = 4$.

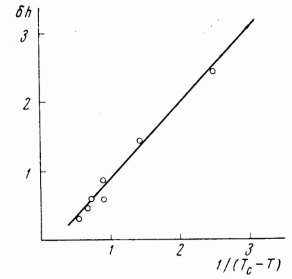

FIG. 9. Plot of $\delta h = (H_{c3}{}^{e}|_{R/R_n=0.995} - H_{c2}{}^{e})/H_{c2}{}^{e}$ against $1/(T_c - T)$.

free path ($l \sim 10^{-8}$ cm). For our samples, $l \approx 5 \times 10^{-8}$ cm (estimated from ρ_n). In [15], in which the influence of thermodynamic fluctuations on the decrease of the resistance below R_n was calculated in the region $H > H_{c2}$, it follows that the relative width $\delta h = (H|_{R=R_n} - H_{c2})/H_{c2}$ of the "smearing" of the transition should increase like $1/(T_c - T)$ as $T \to T_c$ (it is assumed that $(H|_{R=R_n} - H_{c2}) \ll H_{c2}$). As seen from Fig. 9, where δh is taken to be the ratio $(H_{c3}^{e}|_{R/R_n \geq 0.995} - H_{c2}^{e})/H_{c2}^{e}$, the experimental data agree well with this condition. In addition, it should be noted that the value of H_{c3}^{e} depends neither on the direction of the magnetic field (see Fig. 3) nor on the measuring current.

CONCLUSION

Thus, our results cast additional light on the conditions of occurrence and on the nature of the peak effect on the $I_c(H)$ curves near H_{c2}. The investigation of the hysteresis on the current-voltage characteristics has made it possible to explain the experimental situation and to advance the hypothesis that at given H and T there can exist different vortex-lattice configurations, and the realization of any particular configuration depends on the conditions under which the mixed state is established. It was observed experimentally that it is possible to obtain stationary states at which a given value of the current through the sample corresponds to different electric fields. This apparently indicates that in some cases some of the fluxoids may become immobile in the resistive state. The occurrence of the peak effect is connected with the increase, near H_{c2}, of an additional friction force exerted by the pinning centers on the moving fluxoids. Such an increase is apparently the consequence of the change in the elastic properties of the vortex lattice.

The obtained temperature dependence of the ratio H_{c3}^{e}/H_{c2}^{e} allows us to think that too large a "smearing" of the superconducting transitions R(H) at temperatures close to T_c is more readily due to fluctuation phenomena.

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Note added in proof (21 December 1971). A study of the structure of the sample section investigated by us, performed by V. A. Titov by transmission electron microscopy, has shown that the sample contains a rather large number of ω-phase particles, with dimensions on the order of 300Å. It is obvious that it is their presence that leads to the appearance of the observed peak effect. Since ω-phase particles with such dimensions go over completely into the normal state in fields not exceeding 30 kOe, we assume, as before, that the peak effect investigated by us belongs to the first of the types indicated by us.

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