SOVIET PHYSICS
JETP

A translation of the Journal of Experimental and Theoretical Physics of the USSR.

VOL. 1, NO. 2, PP. 197-408 SEPTEMBER, 1955

The Kinetics of the Destruction of Superconductivity by a Magnetic Field *

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(Submitted to JETP editor March 23, 1954)

J. Exper. Theoret. Phys. USSR **28**, 463-470 (April, 1955)

The kinetics of destruction of superconductivity of a cylindrical tin specimen has been studied in audio-frequency alternating magnetic fields and the experimental data compared with theory. A region of values of "supercriticality" has been found, in which the phase transition in the specimen takes place by boundary movement. The times for establishment of a nucleus of normal and superconducting phase are estimated.

A number of experimental studies[1,2] have been made on the kinetics of distribution of superconductivity by a magnetic field. However, it is difficult on the basis of the published data to make a comparison of the experiments with the theory developed by Lifshitz[3,4,**]. It therefore seemed desirable to carry out experiments, the data of which could allow a more detailed comparison of experiment with theory. For this purpose the method of a transformer with a superconducting core[6] was used in a somewhat modified form.

* This work was presented at the Session of the Academy of Sciences of the Ukrainian SSR on April 18, 1952

** In the investigation[5] which agreed with theory, questions of the kinetics of destruction of superconductivity by alternating magnetic fields and also questions of the limits of applicability of the theory are not discussed.

[1] N. E. Alekseevskii, Doklady Akad. Nauk SSSR **60**, 37 (1948)

[2] T. E. Faber, Nature **164**, 277 (1949)

[3] I. M. Lifshitz, J. Exper. Theoret. Phys. USSR **20**, 834 (1950)

[4] I. M. Lifshitz, Doklady Akad. Nauk SSSR **90**, 363 (1953)

[5] T. E. Faber, Proc. Roy. Soc. A **219**, 75 (1953)

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DESCRIPTION OF THE APPARATUS

The secondary coil of the transformer was wound on a glass capillary containing a monocrystalline specimen of tin of initial purity 99.99%. The surface of the glass free from the winding was then dissolved in hydrofluoric acid. Since the winding occupied only 20% of the total surface of the specimen the latter was in good thermal contact with the liquid helium during the measurements. This circumstance and the high thermal conductivity of the specimen ensured that the processes of destruction and restoration of superconductivity were isothermal.

Later the transformer with its superconducting core was improved by putting the secondary winding directly on the solenoid, and the specimen, completely free from glass, was placed along the axis of the transformer. The transfer of the secondary winding from the specimen to the solenoid not only improved the isothermal character of the processes of destruction and restoration of superconductivity, but eliminated systematic errors in determining the "supercriticality" of the alternating field applied to the specimen. These errors arose from the screening action of eddy currents induced in the secondary coil, which led to a dependence of the constant of the solenoid on the frequency of the alternating current flowing in it.

The primary of the transformer, i.e., the solenoid

1 (see Fig. 1) was fed by the 50 watt audio-

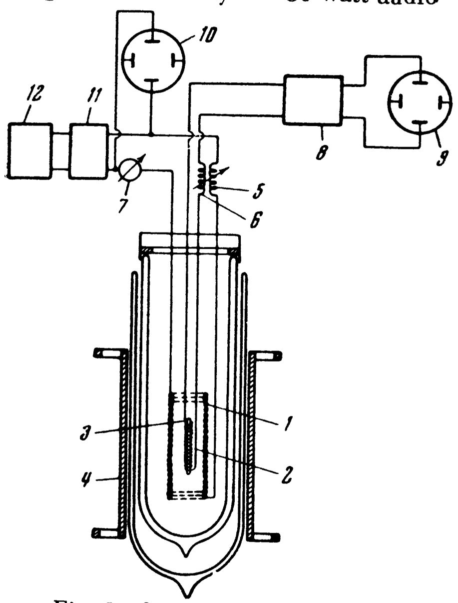


Fig. 1. Scheme of the apparatus.

frequency generator *12* and fields of amplitude up to 200 oersteds could be obtained. The impulses emf produced in the secondary at the instants of destruction and restoration of superconductivity of the tin core *3* were registered by the oscillograph *9*. At medium and extreme audio-frequencies these impulses were considerably distorted by the sinusoidal curve of emf arising from that part of the secondary cross-section not filled with the superconductor. To eliminate this background, a compensating transformer was added to the circuit. The compensation was achieved by varying the coupling between the coils *5* and *6* of the compensating transformer when the core was superconducting. For those frequencies for which compensation of both amplitude and phase could be achieved, the background was reduced practically to zero; in other cases it was considerably reduced.

The sinusoidal form of the current in *1* during the experiment was checked by a special oscillograph *10;* a sinusoidal form was required since the presence of harmonics made good compensation of the background impossible.

The generator, the power amplifier *11* and the wide-band amplifier *8* were supplied by batteries in order to eliminate 50 cycle/sec modulation and to make easier the synchronization of the linear time base of the oscillograph *9*. The current in the primary was measured by an ordinary AC meter. The frequency characteristic of this meter was taken several times and it was established that the meter sensitivity was practically independent of frequency. The calibration of the meter was made in the following way. At a temperature below T_c, a field of the form $H = H_{const} + H_0 \sin \omega t$ was applied with $H_{const} + H_0 < H_c$. Then, keeping H_0 constant, the steady field H_{const} was increased until impulses of emf were just obtained in the secondary corresponding to transitions from superconducting to normal state and vice-versa. The beginning of impulses then corresponds to $H_{const} + H_0 = H_c$ and, since H_c is known as a function of T, the true value of H_0 can be deduced from that of H_{const} (given by the reading of a precision DC meter): the value of I_0, the current amplitude, follows from H_0, and the corrections to the readings of the AC meter could be established. In this way the meter was calibrated over its entire scale and at all frequencies.

RESULTS OF MEASUREMENTS

For frequencies between 10^2 and 2×10^4 cycles/sec at various temperatures and various "supercriticalities" [defined as $u = (H - H_c)/H_c$] of the magnetic field, oscillograms were taken of the emf $E(t)$ in the secondary. A series of such oscillograms obtained at 200 cycles/sec and 3.621° K, in order of ascending u, is shown in Fig. 2 *a - f*. From these it follows that for $u < 0.5$ the "rule of areas" applies, i.e., the area $S = \int_{t_1}^{t_2} E(t)\,dt$ under the impulse for destruction of superconductivity is equal to $S_2 = \int_{t_3}^{t_4} E(t)\,dt$, the area corresponding to restoration of superconductivity. Moreover, either area S increases linearly with the maximum value of u (Fig. 3).

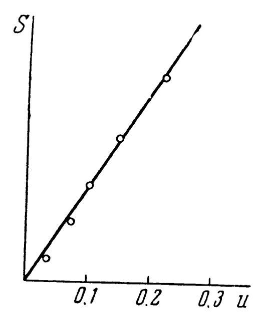
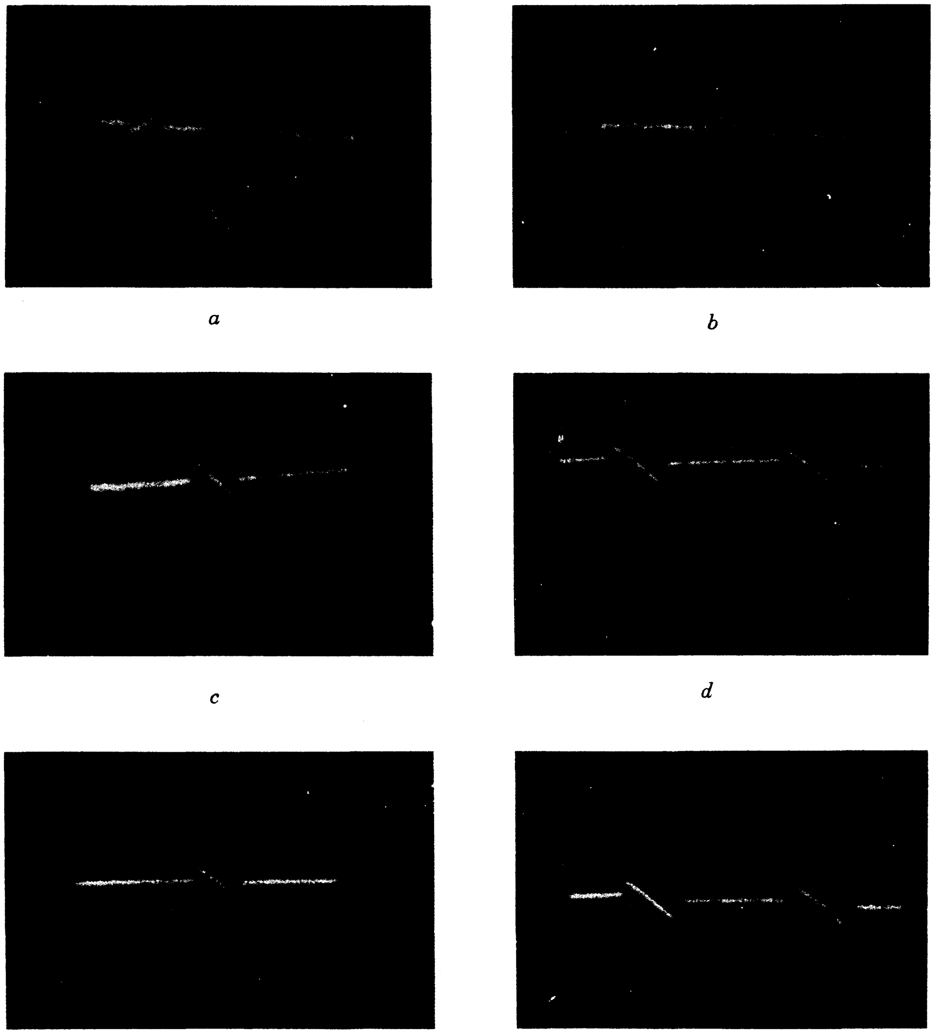


Fig. 3. Dependence of $S = \int E\,dt$ on "supercriticality" u for $\nu = 200$ cycles/sec

For larger values of u (Fig. 4 *a-c*) the oscillograms differ markedly in form from those for smaller u. In these, sharp jumps of emf can be seen in the transitions from the superconducting to the



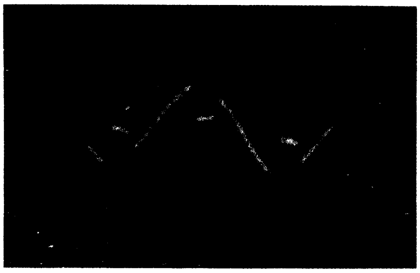
a b c d e f

Fig. 2. Oscillograms of $E(t)$ for $\nu = 200$ cycles/sec, $T = 3.621°$ K and $H_0 = 16.1$ oersteds; H_{const} (in oersteds): $a = 0$, $b = 0.96$, $c = 1.18$, $d = 1.65$, $e = 3.76$, $f = 4.55$

normal state and vice-versa. The impression is that the transition from one state to the other takes place almost without expulsion of the field. In other words, the effects of destruction take place in a very thin surface layer with "freezing-in" of the field inside the specimen.

Figure 5 *a*-*f* shows the oscillograms obtained at 4000 cycles/sec and $T = 3.621°$ K. The amplitude of the alternating magnetic field was held constant throughout at about H_c, and the constant field was increased from zero to H_c. Figure 5 *f* is for the normal state alone, i.e., for $H_{const} > H_c$. From Fig. 5 *a*-*e* the symmetry of the areas $\int E(t)\,dt$ for the processes of destruction and restoration of superconductivity is again established; the "supercriticality" increases with H_{const}, and the area $\int E(t)\,dt$ increases linearly at the same time (Fig. 6).

It is characteristic that for small H_{const} there is some asymmetry of the oscillograms as between the first and second half periods: the impulses corresponding to destruction and restoration of superconductivity in the first half period are not equal to the corresponding impulses in the second half period. It turned out that this effect is connected with the presence of the earth's magnetic field, for



a

b

c

Fig. 4. Oscillograms of $E(t)$ for $\nu = 200$ cycles/sec, $T = 3.621°$ K, H_0 in oersteds : $a = 24.6$, $b = 34.2$, $c = 45.7$

when the latter was compensated by Helmholtz coils, the oscillograms became quite symmetrical. Owing to technical difficulties we did not compensate the earth's field during photography of the oscillograms. From Lifshitz's theory it follows that for values of $H_{const} > H_c$ and for frequencies satisfying the condition $\delta_{skin} < r$, no transition to superconductivity should be observed at instants when $|H_{const} + H(t)| < H_c$. To check this prediction, the following experiment was carried out. The specimen was placed in a field $H_{const} > H_c$ and an alternating field was superimposed, whose amplitude and frequency could be varied. It turned out that for any of the frequencies applied, transitions to the superconducting state did take place, which could be observed by irregularities in the changes of emf in the secondary coil of the transformer. However, for each frequency, a minimum amplitude $H_{0\ min}$ of the alternating field was found, below which no transition took place. As illustrated in Fig. 7, the value of $H_{0\ min} - H_{const}$ increases with frequency.

DISCUSSION OF RESULTS

Lifshitz's theory is valid if there is a large difference between the time of formation of nuclei of the normal and superconducting phases. In this case the processes of destruction and restoration of superconductivity of a specimen in a longitudinal magnetic field take place by radial movement of a phase boundary. From the theory it is easy to obtain quantities which permit a quantitative comparison of the theory with experiment. Thus, Lifshitz showed that the dependence of Φ, the flux embraced by the contour of the specimen, on the maximum "supercriticality" u, should be $\Phi = \propto u^{3/4}$. Experiment gives $\Phi \propto u$. It should be noticed that a departure from the law $\Phi = \propto u^{3/4}$ is given also by the other, independent, measurements[2] in which it was found that the speed of movement of a phase boundary varied with the "supercriticality" rather more strongly than linearly. Thus comparison of the experimental data with theory leads to the conclusion that the dependence of the depth of destruction on "supercriticality" must be stronger than predicted by the theory. A similar discrepancy was

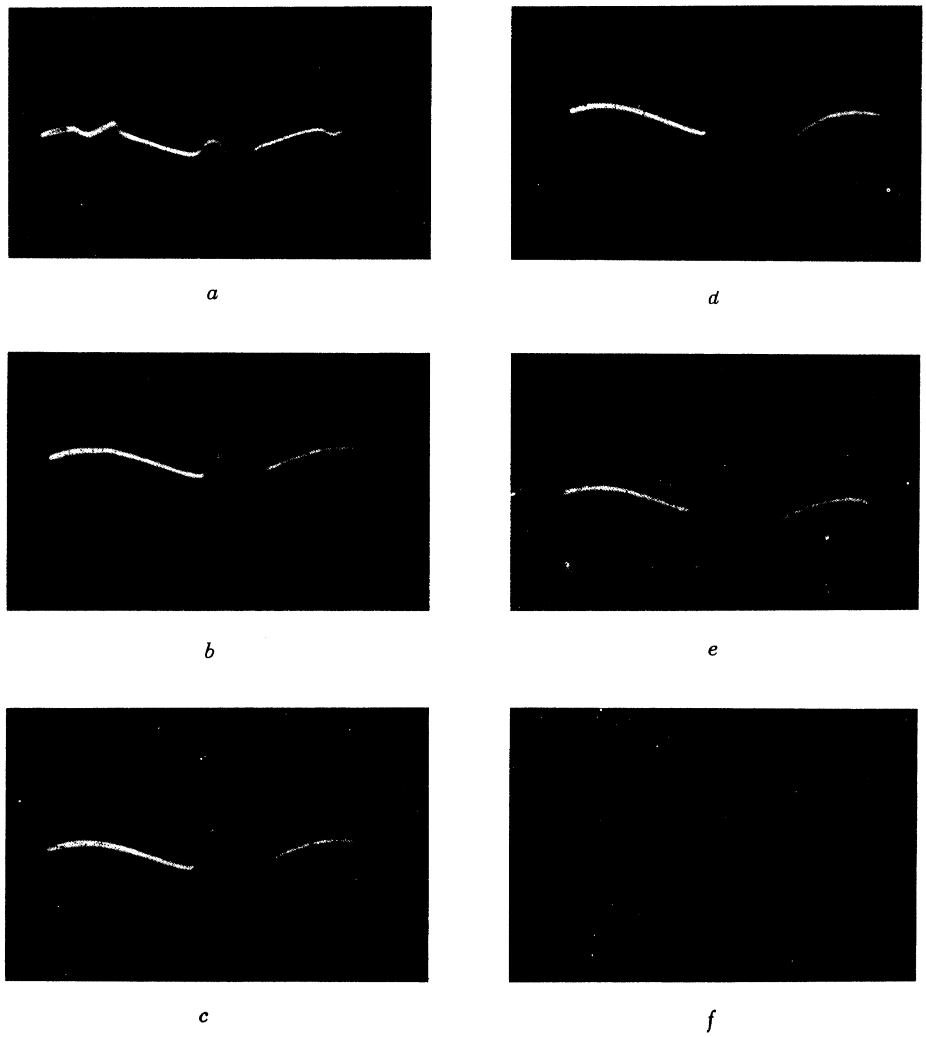


Fig. 5. Oscillograms of $E(t)$ for $\nu = 4000$ cycles/sec, $T = 3.621°$ K and $H_0 \sim H_c$; H_{const} in oersteds: $a = 0$, $b = 0.7$, $c = 1.18$, $d = 1.95$, $e = 2.71$, f = for the specimen in the normal state.

established in experiments on the decay of currents induced in a ring[6].

Since there is some discrepancy between theory and experiment, let us look more closely into the comparison between the experimental results and theory, turning to the numerical values of the various quantities; in particular, the numerical values of the speeds of displacement of the phase boundary.

Consider the flux Φ_1, entering the specimen in destruction of superconductivity and the mean flux Φ_2 penetrating the same contour in the normal state during a quarter period; these fluxes are easily determined from the oscillograms. On the other hand, for small values of u, Φ_1 and Φ_2 are given by

$$\Phi_1 = 2\pi r d H_K;$$

$$\Phi_2 = 2\pi r \frac{4}{T} \int_0^{T/4} \int_0^{\infty} H_0 \sin \omega t \, dt \, e^{-x/\delta} dx = 4r\delta H_0.$$

Here d is the maximum depth of destruction of superconductivity and δ the skin depth of penetration of the alternating field in the specimen. Since in our case $H_0 \approx H_c$, we have $d/\delta = (2/\pi)\,\Phi_1/\Phi_2$.

In table I we compare the values of d/δ obtained from experiment with those based on Lifshitz's theory.

After all the measurements on the specimen had

TABLE I

d/δ	Value of "supercriticality" u			
	0.22 ∓ 0.01	0.23 ∓ 0.01	0.27 ∓ 0.01	0.33 ∓ 0.01
Theor.	0.44	0.48	0.49	0.60
Exper.	0.38 ± 0.04	0.45 ± 0.05	0.48 ± 0.05	0.69 ± 0.07

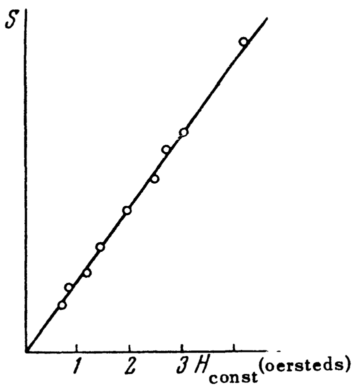


Fig. 6. Dependence of $S = \int E\, dt$ on "supercriticality" u for $\nu = 4000$ cycles/sec.

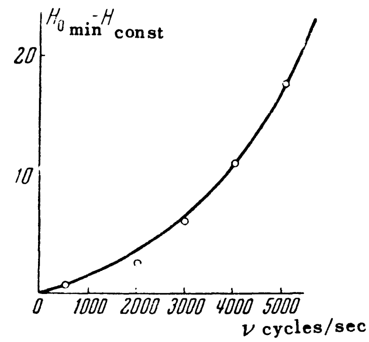


Fig. 7. Dependence of the difference $H_{0\ \min} - H_{\text{const}}$ (arbitrary units) on the frequency

been made, its DC electrical conductivity was determined ($\sigma = 1.2 \times 10^{20}$ cgs units) and from the values of $E(t)$ and σ, the speeds of displacement of the phase boundary could be calculated as a function of "supercriticality". It turned out that for increase of u the discrepancy between calculated and experimentally observed velocities increased, which agrees with the discrepancies found for the maximum depth of destruction. At the same time the theoretical law $v \propto \omega^{1/2}$ is confirmed for $u < 0.6$ at frequencies from 100 to 4000 cycles/sec (tin) and 50 to 500 cycles/sec (mercury). It should be noted that if the mercury oscillograms[6] are analyzed for the same u as for tin,it is found that $v_{\text{Hg}} > v_{\text{Sn}}$, the ratio being $v_{\text{Hg}} / v_{\text{Sn}} = 4.85$,which is just equal to $(\sigma_{\text{Sn}} / \sigma_{\text{Hg}})^{1/2}$. Thus from the data from the two metals we find that v is proportional to $\sigma^{-1/2}$, which together with the relation $v \propto \omega^{1/2}$ gives $v \propto (\omega/\sigma)^{1/2}$.

The exceptional sharpness of the oscillograms and the absence of additional spreading at places corresponding to transitions from one state to another, for all frequencies up to 1.5×10^4 cycles/sec, deserves special mention.

We shall now attempt to estimate an upper limit to the time τ_n for the formation of a nucleus of normal phase, based on the fact that this time must be less than the amount of spread of the line on the oscillogram, i.e., $\tau_n < T\,(\Delta t/T)$, where $\Delta t/T$ is the relative spread of the line on the oscillogram. Since $\Delta t/T \approx 1/60$, it follows that $\tau_n < 10^{-6}$ sec. Of course, this value must be related to the particular value of "supercriticality", since with increase of the latter the time of formation of a nucleus must decrease. Assuming that $u = 0.5$, we find that the "supercriticality" at the transition itself is $u_{s \to n} = 0.5/10 = 5 \times 10^{-2}$.

To explain the sharpness of the oscillograms we might have assumed that $\tau_n > 10^{-2}$ sec. However, the specimen surface would then always be covered with a thin layer of normal material, created at the moment of switching on the alternating field. Such a layer would lead to two consequences which were not experimentally observed: 1) to the existence of irregularities in the oscillograms at the instant of switching on the field, with impossibility of synchronizing the individual acts of destruction, 2) to a strong frequency dependence of velocity of boundary displacement: $v \propto \omega^n$ where $n > 1$.

If we assume that the time of creation of a nucleus of normal phase is less than 10^{-6} sec, the time of destruction of such a nucleus may be considerably greater. Indeed, from oscillograph experiments on the transition curve [7] it was established that if AC flows through a specimen, then for temperatures below T_c it is possible to observe the continuance of the normal state even in those parts of the period where $I(t) < I_c$ (see Fig. 8). This means that in a quarter period the normal state cannot be destroyed, and consequently that $\tau' > 10^{-4}$ sec. Thus we can say that the times of creation τ_n and destruction τ_n' of a normal nucleus are different.

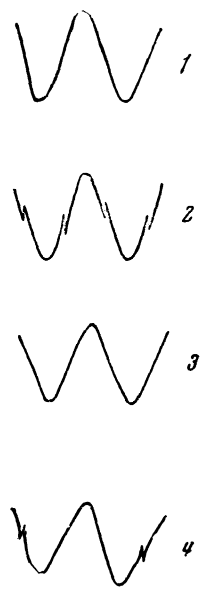


Fig. 8. Oscillograms of $E(t)$ observed on passing a sinusoidal alternating current through the specimen, for temperatures: $1 = 3.725°$ K, $2 = 3.711°$ K, $3 = 3.709°$ K, $4 = 3.7085°$ K. Curves without breaks correspond to the specimen remaining only in the normal state for the whole time.

Consider now a second possibility of explaining the sharpness of the oscillograms. We can suppose that there always exist on the surface of the specimen nuclei of normal phase, located at places of greatest curvature. For instance, in the case of monocrystals the surface has a step-like structure, so that on account of the demagnetizing factor these steps may be in the intermediate state [8]. This means that part of the volume of the monocrystal will provide nuclei of normal phase from which a practically inertialess boundary displacement can originate.

Here, however, we encounter the following kind of difficulty. For stability of a nucleus it is necessary that it should have a certain minimum volume. According to estimates in the work [9], $V_{min} = 4 \times 32^3 \pi^4 \alpha^3 / 27 H_c^6$, where α is the surface tension between normal and superconducting phases. For our case, $V_{min} = 10^{-6}\mathrm{cm}^3$ which agrees well with data obtained by Alekseevskii [10].

As already indicated, only that part of the surface of the specimen can go over into the normal state, in which the intermediate state is realized, i.e., in the regions of step-like structure. Assuming that this structure is oriented to have the largest demagnetizing coefficient, it is possible to estimate the volume V_1 of each little step, and this turns out to be 10^{-8} to 10^{-9} cm^3. Since $V_1 \ll V_{min}$, the formation of a stable nucleus of the new phase is impossible.

Experimentally, the question of the possibility of formation of nuclei at surface irregularities can be decided by investigations with specimens treated in various ways. For an etched surface the conditions for formation of nuclei should be most favorable; for a polished surface least favorable. If the time of formation of a normal nucleus $\tau_n > 10^{-6}$ sec, polishing of the specimen should lead, for certain frequencies, to smearing of the oscillograms. However, measurements on tin specimens in glass envelopes and etched specimens do not give appreciably different results. We are therefore inclined to conclude that $\tau_n < 10^{-6}$ sec.

As already mentioned, the theory gives the correct frequency dependence of velocity of boundary displacement for small "supercriticality", but starting with a maximum "supercriticality" $u > 0.6$ an appreciable departure of the experimental data

[7] A. A. Galkin and B. G. Lazarev, J. Exper. Theoret. Phys. USSR **18**, 833 (1948)

[8] N. E. Alekseevskii, J. Exper. Theoret. Phys. USSR **16**, 870 (1946)

[9] P. Bulashevich, J. Exper. Theoret. Phys. USSR **8**, 1267 (1938)

[10] N. E. Alekseevskii, Dissertation, Institute for Physical Problems, Academy of Sciences of the USSR, Moscow, 1948

from the theoretical prediction sets in*. This appears particularly clearly with thin specimens, for which the departure sets in for even smaller values of u.

From the oscillograms taken for $u > 0.6$ it follows that the specimen is in the normal state for the greater part of the time. Indeed, if on an oscillogram taken in these conditions,one taken entirely in the normal state is superposed, they coincide with each other over practically the whole period. The transitions from state to state last only a short time and are not accompanied by large emf's. On the narrow portions of the oscillogram corresponding to the transition from the normal to the superconducting state, the emf diminishes to a value corresponding to the superconducting state. This characteristic of the oscillogram can be explained in the following way: if the field at the surface becomes less than critical (while remaining critical inside), then conditions arise for formation of superconducting nuclei at the surface, which grow over the whole surface and lock in the magnetic field in the interior. Consequently, destruction and restoration of superconductivity takes place in a thickness d, appreciably less than the skin depth δ_{skin}. Thus, the mechanism of destruction considered by Lifshitz is apparently not applicable in this case.

By investigating the process of destruction of superconductivity by an alternating magnetic field, it should in principle be possible to establish a regime, starting from which the mechanism of boundary displacement is replaced by the nucleation mechanism, and in this way to estimate the time of formation of a superconducting nucleus. However,since measurements of the dependence of $\int E(t)\,dt$ on "supercriticality" do not give a reliable determination of the exact moment of the beginning of the transition from one mechanism to the other, the time of formation of a superconducting nucleus should, in our opinion, be estimated from the following considerations.

For $H_{const} > H_c$, an unlimited progressive movement of the boundary inside the superconductor sets in. The presence of an alternating component $H(t)$ superimposes an oscillation of the boundary on its steady motion. In the case of a cylindrical specimen, for fields greater than H_c, it will be completely in the normal state . At certain instants the field at the surface will be less than critical, and conditions are suitable for the transition to the superconducting state.

Investigations carried out along these lines showed that the value of the field H_0, for which a transition to superconductivity begins to set in, is related to the frequency by the relation

$$u' = (H_\kappa - H_0) / H_\kappa = \alpha\omega^2 \quad \text{or} \quad u'T^2 = \text{const}.$$

From Fig 9 the time necessary for formation of a superconducting nucleus in the case of sudden removal of the field can be found . The duration of formation of a superconducting nucleus in these conditions turns out to be $\tau_s = 1.5 \times 10^{4}$ sec.

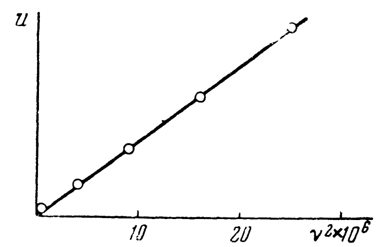


Fig. 9.

CONCLUSIONS

1. It is shown that the velocity of displacement of the boundary between normal and superconducting phases, follows the law $v \propto (\omega/\sigma)^{1/2}$ in agreement with theory.

2. The depth of destruction of superconductivity by an alternating magnetic field depends linearly on "supercriticality", which disagrees with the theoretical prediction $(d \propto u^{3/4})$.

3. Some discrepancies between the theoretical and experimental values of the velocity of boundary movement may be explained by the linear dependence of the depth of destruction on "supercriticality".

4. It is experimentally established that the times of τ_n, τ_s of formation of a nucleus of the superconducting and normal phase are different. In agreement with the assumption of Lifshitz's theory,it is found that $\tau_s \approx 1.5 \times 10^{-4}$ sec, $\tau_n < 10^{-6}$ sec.

5. The asymmetry of the processes of growth and

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* It should be noted that the region of " supercriticality " for which Lifshitz's theory might be expected to hold, is limited not only from above, but also from below. Its lower limit is $\Delta H/H_c$ where ΔH is the breadth o the field interval over which the transition from one state to the other occurs. It seems to us that a number of the results of a recent investigation [see T. E. Faber, Proc. Roy. Soc. A 219, 75 (1953)] can be explained by supposing that in this investigation "supercriticalities" were used for which $u < \Delta H / H_c$.

collapse of nuclei of the normal phase is experimentally demonstrated.

In conclusion we express our deep gratitude to Professor B. G. Lazarev and Professor I. M. Lifshitz for their interest in this work and discussion of the results obtained, and also to A. I. Berdovskii for help in the measurements.

Translated by D. Shoenberg
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SOVIET PHYSICS - JETP VOLUME 1, NUMBER 2 SEPTEMBER, 1955

The Velocity Distribution of Electrons in the Presence of a Varying Electric Field and a Constant Magnetic Field

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(Submitted to JETP editor March 9, 1954)
J. Exper. Theoret. Phys. USSR **28**, 422-430 (April, 1955)

The function of the velocity distribution of electrons in the presence of a varying electric field and a constant magnetic field is found. Two cases are examined: 1) an electric field depending harmonically on time; 2) an amplitude-modulated electric field.

1. INTRODUCTION

THE problem of finding the function for the velocity distribution in the case of elastic collisions of electrons with the atoms of a gas has been analyzed by several authors[1-5]. The basic work on this question appears to be that of Davydov[1]. In this work the function of the distribution of electrons in the presence of constant electric and magnetic fields was obtained. Margenau[3] analyzed the action in a varying electric field. The influence of a constant magnetic field in the presence of a varying electric field was examined by Jancel and Kahan[5]. However, they did not take into account the action of the components of the electric field parallel to the direction of the magnetic field.

In the works mentioned, the influence of the collision of electrons with each other was not considered. Meanwhile, as was shown by Cahn[6], the influence of inter-electronic collisions must be accounted for in the case of a constant electric field if the concentration of electrons is great.

In Part 2 we will give an analysis of the distribution function of the electrons according to velocity in the presence of an electric field, harmonically dependent on time, and a constant magnetic field.

In Part 3 we shall analyze the action in an amplitude-modulated electric field.

2. THE DISTRIBUTION OF ELECTRONS IN THE PRESENCE OF A HARMONIC ELECTRIC FIELD AND A CONSTANT MAGNETIC FIELD

Assuming that a gas is uniformly distributed in space, the kinetic equation takes the following form:

$$\frac{\partial f}{\partial t} + \mathbf{a}\,\nabla_v f = \frac{\delta}{\delta t} f, \tag{1}$$

where $f(\mathbf{v}, t)$ is a function of the velocity distribution of the electrons, $\mathbf{a}$ is the acceleration communicated by the field of electrons, $\partial f/\partial t$ denotes the rate of the change of the distribution due to the presence of the field, $(\delta/\delta t)f$ stands for the collision of electrons with gas atoms (the effects of the collision of electrons with each other are not considered)*, ∇_v is the gradient in the velocity domain. In our case

$$\mathbf{a} = \frac{e}{m}\mathbf{E}_0\Theta + \frac{e}{mc}[\mathbf{vH}] \equiv \vec{\Gamma}\Theta + \frac{e}{mc}[\mathbf{vH}], \tag{2}$$

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* The effect of inter-electronic collisions is not essential when the concentration of electrons is not very great and the field frequencies are high[6,8].