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Flux-Flow Noise in a Type-I Superconductor

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The noise voltage across a current-carrying type-I superconductor is attributed to flux flow. Measurements of power spectra of this flux-flow noise on In–2 at.% Pb foils show that the noise spectrum has a $1/f^\alpha$ frequency dependence with $0.5<\alpha<1$. This can be accounted for by a model in which the flux moves in a jerky manner because of interaction with immobile normal regions. This causes a distribution of voltage-pulse duration times. It is concluded from the power spectra that the dc voltage V is caused by a flux-flow component and an ohmic-loss voltage in immobile normal regions. The flux-flow fraction of the dc voltage is found to be a rapidly decreasing universal function of V/V_n, where V_n is the normal-state voltage. The size of the moving normal domains is calculated from the noise voltage and the dc voltage, and is shown to increase with field in a range from $10^3\phi_0$ to about $10^5\phi_0$. At low fields, flux presumably moves as bundles of small flux tubes, as in type-II superconductors. Close to T_c a structure is found in the power spectra which may be associated with the motion of vortex rings.

1. INTRODUCTION

Although the phenomenon of flux flow generating an electric field was first proposed[1] for type-I superconductors, the experimental and theoretical work on flux flow has almost exclusively been devoted to type-II superconductors. This is probably due to the fact that no experimental evidence for flux flow in type-I superconductors was available and because the structure of the intermediate state is much more complicated than that of the mixed state.

In theoretical models it is often assumed that in the intermediate state the normal (n) and superconducting (s) domains are in the form of parallel layers extended in the field direction. The response of this structure to the application of a transport current has been under discussion for some time. London[2] concluded from the continuity of the tangential component of the local electric field $\mathbf{e}$ at the n-s boundary and because $\mathbf{e}=0$ in a superconductor, that the n and s domains would be placed perpendicular to an electric field. This would mean that, when a current is applied, the boundaries set themselves perpendicular to the current if the Hall effect can be neglected.

Experiments involving powder techniques[3–5] confirmed this model. To explain the strong dependence of resistance on measuring current, it had been suggested by Shoenberg[6] that at low currents the s and n laminae might be parallel to the current and at high currents perpendicular to it. It was noted, however, that such a situation at low currents would be unstable because the normal domains would start moving in a direction perpendicular to current and field. In noting this, Shoenberg was the first to suggest the phenomenon of flux motion in a superconductor.

Gorter[1] also suggested that the intermediate state consists of s and n layers parallel to magnetic field and current. Because of a Lorentz force, the layers will move with velocity v. The electric fields in s and n layers, respectively, are then

$$\mathbf{e}_n=-(\mathbf{v}\times\mathbf{b})/c=-(\mathbf{v}\times\mathbf{H}_c)/c\,,\quad \mathbf{e}_s=0\,, \tag{1}$$

where $\mathbf{b}$ is the induction in the normal layers, and $\mathbf{H}_c$ has the magnitude of the critical field and the direction of the applied field.

If $\mathbf{B}$ is the average induction, the average electric field in the superconductor is

$$E=-(\mathbf{v}\times\mathbf{B})/c=-\beta(\mathbf{v}\times\mathbf{H}_c)/c\,, \tag{2}$$

where $\beta=B/H_c$ is the normal fraction.

The current density can be written

$$J=\sigma E/\beta \tag{3}$$

if σ is the normal-state conductivity. The effect of pinning can be accounted for by replacing J by $(J-J_c)$, where J_c is the critical current density for flux motion. If we write for the balance of forces on an isolated normal region with flux content φ, neglecting the Hall effect

$$(J-J_c)\varphi/c=\eta v\,, \tag{4}$$

where η is a viscosity coefficient, it follows that

$$\eta=\varphi H_c\sigma/c^2\,. \tag{5}$$

The velocity can be written

$$v=(J-J_c)c/\sigma H_c\,. \tag{6}$$

It increases with magnetic field and with temperature by the field and temperature dependence of J_c and the temperature dependence of H_c.

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[2] F. London, *Superfluids I, Macroscopic Theory of Superconductivity* (Dover Publications, Inc., New York, 1961), p. 110.
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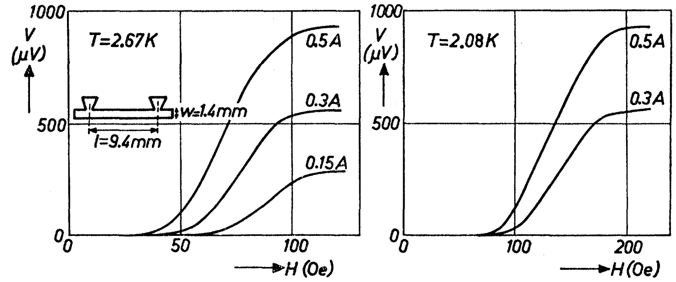

FIG. 1. dc voltage versus perpendicular field for In–2 at.% Pb foil at various values of the transport current, $T=2.67$ and 2.08°K. Inset: Shape of the specimen.

Andreev and Sharvin[7] have given a macroscopic description of the intermediate state in the presence of a transport current, taking into account the magnetic field caused by the current. From the relation $v=-cE/H$ they obtain the following expression for the velocity of a laminar structure in the case of a superconducting slab in a perpendicular field:

$$v=(-c^2/4\pi\sigma a)\arcsin(4\pi Ja/cH_c), \tag{7}$$

where $2a$ is the thickness of the slab.

This expression reduces to Eq. (6) for small values of J and if J is replaced by $(J-J_c)$.

Recently, different types of experiments have shown that at low fields flux flow takes place under the influence of a Lorentz force. This was demonstrated by measurements of coupling of flux motion in a thin film sandwich,[8] voltage oscillations between a point contact and a superconductor[9] (these experiments have, however, been criticized as not being unambiguous proof of flux motion[10,11]) flux-flow noise,[12] Ettingshausen,[13] and Nernst effects.[14]

A direct proof of the occurrence of flux motion was given in microscopic observations by Severijns[15] and by Traüble and Essmann.[16]

The recent microscopic work[5,16–18] has shown that the intermediate state may have an extremely complicated structure which depends on whether the intermediate state was reached, coming from the superconducting or from the normal state. At low fields, flux penetrates as isolated flux tubes, some of which may be pinned. When the field is increased the normal regions grow and their cross sections become elongated; there is then a wide distribution of normal-domain sizes with intricate and often meandering shapes.

The effect of a transport current is presumably the following. At low fields the normal flux tubes are isolated and flux flow will take place, thereby generating an electric field, as suggested by Gorter. When at higher fields the normal domains grow and become laminae, their probability of being pinned is smallest if they orient themselves with their long direction parallel to the direction of motion. When such a normal region has a length comparable to the width of the specimen, the transport current has to go through it, thereby generating an ohmic dc voltage. The situation is then, presumably, that domains of different shape and size are stuck in the superconductor, thereby interacting with small domains that can still move and produce a flux-flow voltage. At high fields the stable position of the domains is perpendicular to the current.

Since flux flow generates a noise voltage, as was shown for type-II superconductors,[19,20] measurements of this noise should give information on the same process in type-I superconductors. In this paper we describe measurements of the flux-flow noise voltage in a type-I superconductor. This work is an extension of some preliminary measurements, reported earlier.[12]

2. EXPERIMENTAL

Measurements were done on foils of In–2 at.% Pb. This material is a type-I superconductor with $\kappa=0.35$.[21] This alloy was chosen because it has a high resistivity, so that the noise voltage, which is proportional to the dc voltage, will be measurable. The alloy was melted in a quartz crucible and rolled to a thickness of 45 μ. After the rolling, specimens were cut in the shape shown in Fig. 1 and annealed at about 120°C. They were then glued to a polystrene holder and current and potential leads were soldered. The critical temperature was 3.47°K and the normal-state resistivity at 4.2°K was

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[14] R. P. Huebener, Phys. Letters **24A**, 651 (1967); Solid State Commun. **5**, 947 (1967).
[15] Referred to in Ref. 12.
[16] H. Träuble, and U. Essmann, Phys. Status Solidi **25**, 395 (1968).
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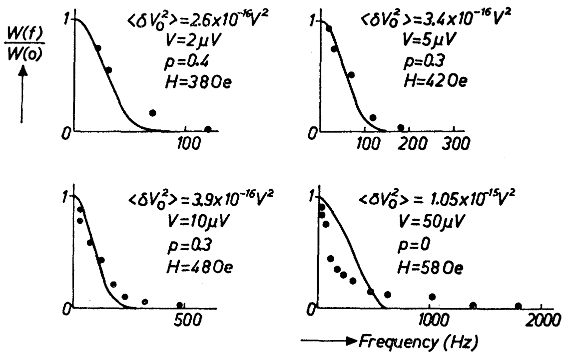

FIG. 2. Experimental noise power spectra on a linear scale normalized at $W(0)$ at different values of the magnetic field, $I=0.3$ A, $T=2.67$°K. The drawn line is the spectrum given by Eq. (9) calculated with a value of p as indicated. The figures also give the values of the extrapolated mean-square noise voltage $\langle\delta V_0^2\rangle$ and the dc voltage V.

1.2 $\mu\Omega$ cm. The critical field is assumed to be given by $H_c=H_0(1-T^2/T_c^2)$ with $H_0=310$ Oe.[21]

The dc voltage V as a function of external perpendicular field H is shown in Fig. 1 for different values of transport current. At low fields, no voltage is found. Apparently, no flux motion takes place because of the pinning of the small normal domains.

The magnetic field for the dc and the noise measurements was generated either by a copper-wound coil or by a pair of Helmholtz coils outside the Helium Dewar vessel.

The noise power spectra were measured with the same set-up as that used for measurements on type-II superconductors.[19,20]

3. FLUX-FLOW NOISE

If the dc voltage across the superconductor is caused by moving flux units of magnitude φ, which are assumed to be independent of each other and generated at random times, then a noise voltage is generated. The power spectrum is dependent on the shape of the elementary voltage pulse generated by a flux unit during its movement from one side of the superconductor to the other.

If we assume for simplicity a rectangular pulse

$$V(t)=\varphi/c\tau \quad \text{for} \quad 0\leqslant t\leqslant\tau, \tag{8}$$

the noise spectrum is[19,20]

$$\langle\delta V_f^2\rangle=(2\varphi V/c)(\sin\pi f\tau/\pi f\tau)^2 df, \tag{9}$$

where $\langle\delta V_f^2\rangle$ is the mean square voltage in the frequency range between f and $f+df$, τ is the transit time for the flux units across the superconductor, and V is the dc voltage.

If we write $v=w/\tau$, where w is the width of the specimen and if there is a fraction of flux p that is pinned and does not take part in the motion, it follows from Eq. (2) that

$$\tau=lwB(1-p)/Vc, \tag{10}$$

where l is the length between the potential probes.

Figure 2 shows some experimental power spectra measured at $T=2.67$°K, with a transport current $I=0.3$ A. The spectra are compared with the theoretical spectrum $W(f)=\langle\delta V_f^2\rangle/df$ of Eq. (9).

At low fields the agreement between theory and experiment is reasonable and a small value of p is found. At fields closer to H_c a negative value of p is found, which has no physical meaning. The model of a flow of flux generating a dc voltage V which satisfies (10) is therefore only applicable to the experiments at low fields.

A second discrepancy at the higher fields between theory and experiment concerns the shape of the power spectrum. The measured spectrum exhibits a long tail at high frequencies. The frequency dependence of the noise power is better demonstrated on a log-log plot, as is given in Fig. 3 where power spectra are shown for various values of the magnetic field with $I=0.3$ A. The maximum noise level was found to be little dependent on current. The measured power spectra cannot be attributed to thermal effects, as was shown by cooling the specimen through the He λ point. The spectra were practically identical at $T=2.21$ and 2.15°K.

The experiments show that in intermediate fields the noise spectra vary with frequency roughly as $1/f^\alpha$ with $0.5<\alpha<1$, whereas at low and at high fields they are similar to the spectrum of Eq. (9).

A change in temperature was found to have very little effect on the shape of the spectrum.

There are thus two discrepancies between theory and experiment, namely, the value of the transit time and the shape of the spectrum.

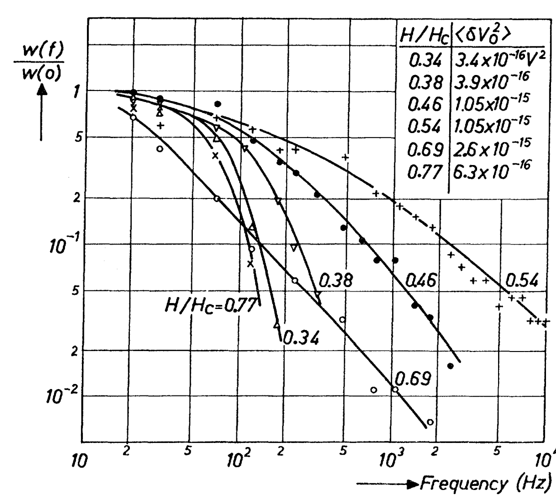

FIG. 3. Log-log plot of experimental noise power spectra normalized at $W(0)$ at different values of the reduced magnetic field H/H_c. $I=0.3$ A, $T=2.67$°K. The figure also gives the value of the extrapolated mean-square noise voltage $\langle\delta V_0^2\rangle$.

A. Distribution of Pulse Duration Times

It will first be discussed how the noise power spectrum is modified if there is a distribution of pulse duration times so that the voltage pulses are not identical.

In not too low fields the intermediate state consists of normal domains of different shapes and sizes. Big normal domains, especially those that extend across the superconductor, are immobile and the current has to go through them. The immobile domains may have complicated shapes and may be oriented at some angle with the flux-flow direction.

The movement of smaller domains will now be interrupted when they strike a large immobile normal region. The flux motion will be continued on the other side of such a region where a small domain may be split off. The motion of flux units will therefore be jerky.

It is now assumed that a flux unit of size φ, when crossing the superconductor, is halted a number of times, but only for such short times that to a first approximation the total transit time is not affected. In other words, the average velocity $v=w/\tau$ is the same for all flux units. This is illustrated in the inset of Fig. 4. We now have

$$W(f)=\int_\epsilon^\tau g(\tau_i)W(f\tau_i)d\tau_i, \tag{11}$$

where $g(\tau_i)$ is a distribution function of pulse duration, $W(f\tau_i)$ is the power spectrum generated by voltage pulses with duration τ_i, and ϵ is some lower limit to the pulse duration time.

(1) We first assume $g(\tau_i)=\text{const}$. This means that all times have equal probability of occurrence in the range $\epsilon\leqslant\tau_i\leqslant\tau$, where $\epsilon\ll\tau$. With the normalizing condition

$$\int_\epsilon^\tau g(\tau_i)d\tau_i=1 \tag{12}$$

we obtain

$$g(\tau_i)=1/(\tau-\epsilon)\approx 1/\tau. \tag{13}$$

If we take $W(f\tau_i)$ as the power spectrum of rectangular pulses, we have

$$W(f\tau_i)=(2\varphi V/c)(\sin\pi f\tau_i/\pi f\tau_i)^2, \tag{14}$$

so that

$$W(f)=(2\varphi V/c\tau)\int_\epsilon^\tau(\sin\pi f\tau_i/\pi f\tau_i)^2 d\tau_i. \tag{15}$$

If we assume $\epsilon=0$ we may write as an approximate solution

$$\frac{W(f)}{2\varphi V/c}=\frac{Si(2\pi f\tau)}{\pi f\tau}-\left(\frac{\sin\pi f\tau}{\pi f\tau}\right)^2, \tag{16}$$

where

$$Si(x)\equiv\int_0^x(\sin t/t)dt.$$

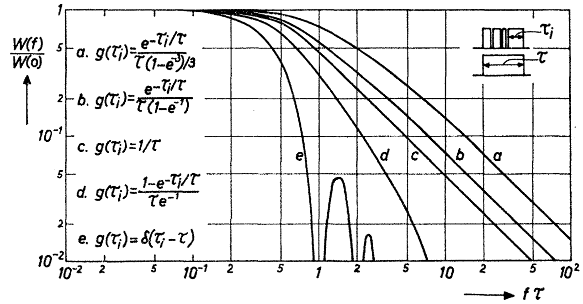

FIG. 4. Theoretical noise power spectra

$$W(f)/W(0)=\int_0^\tau g(\tau_i)[(\sin\pi f\tau_i)/\pi f\tau_i]^2 d\tau_i$$

for various distributions of duration times $g(\tau_i)$ of rectangular pulses. Inset: Voltage pulses with and without halting, transit time τ. In the numerator of distribution a τ_i should read $3\tau_i$.

This approximation is justified for frequencies below $1/\epsilon$. The power spectrum (16) has been calculated numerically with the help of tables published in the literature[22,23] and is shown in Fig. 4, curve c as a function of $f\tau$. For high frequencies, the spectrum varies as $1/f$ and for low frequencies it is a constant.

(2) The spectrum has also been calculated for a distribution function of τ_i with predominantly short pulses, for which is chosen

$$g(\tau_i)=\gamma\exp(-\tau_i/\tau_1), \tag{17}$$

with

$$\gamma=\{\tau_1[1-\exp(-\tau/\tau_1)]\}^{-1}$$

as follows from normalization and τ_1 is a constant. This calculation was done on a computer for $\tau_1=\frac{1}{3}\tau$ and for $\tau_1=\tau$ and assuming $\epsilon=0$. The results are shown in Fig. 4, curves a and b.

At high frequencies the spectra follow a $1/f$ frequency dependence and at low frequencies the spectrum is constant. The spectra are shifted to higher frequencies with respect of the spectrum of (16), because by the different distribution function more short pulses are assumed, but the shape is not much different.

(3) The spectrum for a distribution function with predominantly long pulses

$$g(\tau_i)=\zeta[1-\exp(-\tau_i/\tau_1)], \tag{18}$$

with

$$\zeta=\{\tau+\tau_1[\exp(-\tau/\tau_1)-1]\}^{-1}$$

as follows from normalization, has been calculated using Eqs. (16) and (17) for $\tau_1=\tau$ and is drawn in Fig. 4, curve d.

(4) If for the distribution function a δ function is taken:

$$g(\tau_i)=\delta(\tau_i-\tau'), \tag{19}$$

the spectrum is simply given by (14) with $\tau_i=\tau'$. This is also shown in Fig. 4, curve e for $\tau'=\tau$.

[22] Jahnke-Emde-Losch, *Tafeln Höherer Funktionen* (Teubner Verlag. Stuttgart, 1960).
[23] J. Sherman, Z. Krist. 85A, 404 (1933).

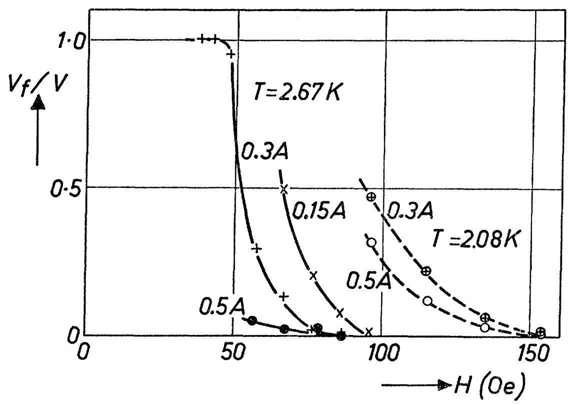

FIG. 5. Flux-flow fraction of the dc voltage V_f/V versus magnetic field at various values of the transport current. $T=2.67$ and 2.08°K.

Comparison of Figs. 3 and 4 shows that the experimental power spectra at low and high fields have a shape that is similar to a spectrum with one transit time, as calculated with Eq. (19).

At low fields there are only small flux units present and no interaction with immobile areas takes place. There is thus only one transit time, and Eq. (19) applies with $\tau'=\tau=w/v$.

At high fields, where the immobile domains are oriented perpendicular to the current, some flux is presumably flowing in between the normal domains, without being halted. Apparently the distribution function for these pulses also resembles a δ function.

In intermediate fields the experimental spectra have a shape similar to those calculated with Eqs. (13), (17), or (18). The model of a wide distribution of pulse lengths is, therefore, qualitatively in agreement with the experiments. As the shape of the spectra is not very sensitive to the choice of the distribution function, it is not possible to make a quantitative comparison between theory and experiment.

B. Determination of the Flux-Flow Voltage

There is also a discrepancy between the value of τ as calculated from the dc voltage with Eq. (10) and the experimental value, except at low fields. The experimental value of τ may be considerably smaller than the calculated value.

This difference is probably caused by the mixed character of the dc voltage. We make the assumption that part of the voltage is caused by ohmic loss in immobile normal regions and does not have a measurable noise component associated with it. The Johnson noise, which is several orders of magnitude less than the noise level that we measured, is neglected.

We now write for the voltage due to flux flow, assuming $p=0$,

$$V_f=lwB_f/\tau c\,, \tag{20}$$

where $B_f=(1-\nu)B$ and ν is the fraction of flux that is contained in immobile, normal regions through which the current flows.

The total dc voltage is

$$V=V_f+V_l\,, \tag{21}$$

where V_l is the ohmic-loss voltage.

The value of V_l cannot be derived from dc experiments, but can be calculated if B_f and τ are known. We assume that ν is proportional to the ohmic-loss voltage

$$\nu=V_l/V_n\,, \tag{22}$$

where V_n is the normal-state voltage. It we write $f_c=1/\tau$, it follows from Eqs. (20) to (22) that

$$V_f=lwBf_c\frac{V_n-V}{cV_n-lwBf_c}. \tag{23}$$

The determination of f_c from the measured noise power spectra is uncertain, as the analytical expression of the spectrum is unknown. We have taken as a somewhat arbitrary criterion the frequency where the mean-square noise voltage has dropped by a factor of 3, relative to the low-frequency level.

The flux-flow voltage was calculated with Eq. (23) for various values of the magnetic field and transport current at temperatures $T=2.67$ and 2.08°K.

The results are shown in Fig. 5, where the flux-flow component of the dc voltage V_f/V is plotted as a function of field. At low fields the dc voltage is caused entirely by flux flow. As the field is increased, an increasing fraction of the dc voltage is caused by ohmic loss and at high fields no flux-flow voltage is left.

These curves are similar to the field dependence of the coupling parameter between two films as measured by Solomon.[8,13] This parameter can be interpreted as the flux-flow fraction of the dc voltage. The results are also in agreement with the drop at high fields of the Ettingshausen[13] and Nernst[14] effects, which are caused by flux motion.

The effect of increasing the current is that a given value of V_f/V is now found at a lower field. Since it follows from Fig. 1 that the same is true for V/V_n, this suggests that the flux-flow voltage fraction is determined by the value of V/V_n. We, therefore, plotted V_f/V as a function of V/V_n in Fig. 6 for the same combinations of current, field, and temperature as in Fig. 5. It can be seen that the experimental points roughly fall on one curve so that V_f/V can be written as a function of V/V_n only.

The conclusion that flux flow takes place only at low fields is supported by microscopic observations[12] of superconducting Nb powder on a current-carrying superconducting Pb foil at $T=4.2$°K in a perpendicular field.[24] The motion of the Nb particles between the edges of the superconductor was observed for different values

[24] These experiments were done in cooperation with A. P. Severijns.

of field and current, and the dc voltage across the foil was recorded at the same time.

It was found that when the field was increased, that the Nb particles started to move in a direction perpendicular to current and field as soon as dc voltage could be detected across the Pb foil. This was proof of the flux-flow character of the dc voltage at low fields. When the field was increased further the dc voltage was increasing continuously, but the number of moving particles was seen to go through a maximum, and the Nb particles came to a standstill long before the critical field was reached, so that at high fields no flux motion could be detected.

The flux-flow velocity, calculated from the noise cut-off frequency by writing $v=wf_c$, was found to go through a maximum as a function of field. This is in disagreement with Eq. (6) according to which v should increase with field. The decrease at high fields may be caused by an enhanced viscosity. It was originally assumed that the normal domains have no interaction with each other and the friction is caused by the motion of the domain itself. In high fields, however, the normal domains may experience additional friction, due to interaction with other domains, so that then the viscosity increases.

The experiments showed that the maximum velocity increases with transport current and with temperature, as should be expected from Eq. (6). Velocities of up to 60 cm/sec were found in the present experiments.

C. Domain Size

The size of the moving flux units can be determined from the value of the noise power, extrapolated to zero frequency:

$$W(0)=2\varphi V_f/c. \qquad (24)$$

This was done from measurements of $W(0)$ and calculations of V_f as described in Sec. B.

The cross-section area S of the flux domains can be written

$$S=\varphi/H_c. \qquad (25)$$

The values S and of φ/ϕ_0 are given in Fig. 7 as a function of magnetic field at $T=2.67$ and 2.08°K and at different values of the current. The value of S increases with field and varies in the measurements at 2.67°K from about 2×10^{-6} cm^2 [which is $(14\,\mu)^2$] to

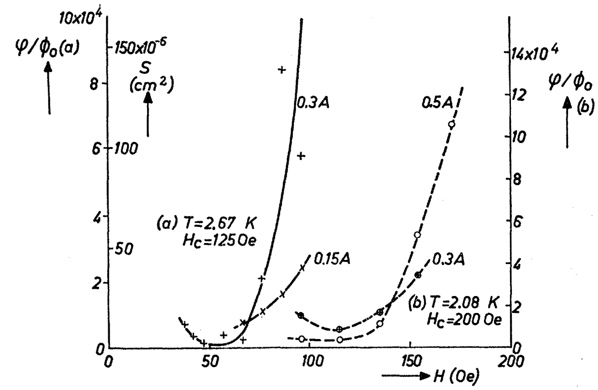

FIG. 7. Cross-section area S and number of flux quanta φ/ϕ_0 of moving flux domains versus field at various values of transport current, $T=2.67$ and 2.08°K.

about 150×10^{-6} cm^2 [which is $(120\,\mu)^2$]. These values correspond to approximately 10^3 to 10^5 flux quanta. At $T=2.08$°K the domains tend to be somewhat bigger.

The results for low fields are similar to those in type-II superconductors, as described earlier.[20] The flux units decrease with increasing field, current, and temperature. In type-II superconductors this behavior was thought to be associated with pinning centers in the material. If the situation is similar in a type-I superconductor this would mean that at low fields the flux is flowing in bundles of isolated flux tubes. An increase of field, current, or temperature would result in smaller bundles.

At higher fields the normal domains grow, so that the values of S and φ/ϕ_0 then increase with field.

D. Low-Frequency Structure

Power spectra were also measured on various specimens at temperatures close to T_c ($T/T_c\approx0.95$).

The spectra exhibited one or more sharp maxima at frequencies below 50 Hz. The origin of this structure is rather puzzling. At lower temperatures it was not found. The maxima are found for different values of the transport current but the height of the maxima is not much dependent on the current.

The structure was also present at low values of the power dissipation in the foil, below the nucleate-boiling limit, and should, therefore, not be attributed to temperature fluctuations.

A possible explanation should perhaps be sought in terms of shrinking vortex rings that are generated by the transport current.[25] The value of the magnetic field where the transition to the normal state occurs, is very low, close to T_c, so that the magnetic field generated by the transport current can then no longer be neglected. If this motion of vortex rings is periodic, the power spectrum should exhibit maxima.

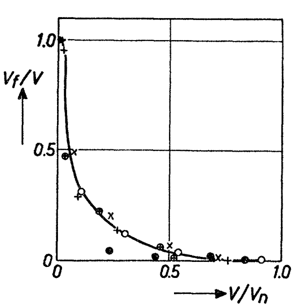

Fig. 6. Flux-flow fraction of the dc voltage V_f/V versus voltage fraction of normal-state voltage V/V_n. The symbols correspond to the values of crrent and temperature in Fig. 5.

[25] C. J. Gorter and M. L. Potters, Physica, 24, 169 (1958).

At lower temperatures the effect of moving vortex rings is negligible compared with ordinary flux flow.

4. DISCUSSION AND CONCLUSIONS

In the explanation of the experimental results we have not mentioned a few effects which may be present, but have been disregarded for simplicity. It is believed that these effects do not play any major role in the determining the noise spectrum.

(1) Flux modulation noise due to fluctuations of the size or the velocity of the moving flux units may be present. There is some experimental evidence for variations of direction of flux motion and of the absolute value of the velocity.[16] These effects presumably give some additional high-frequency noise.

(2) A distribution of transit times may be caused by a flux-flow velocity distribution due to variations in critical current density over the specimen. This too gives some additional noise at the high-frequency side of the spectrum.

(3) Fluctuations of the size of immobile normal domains may give rise to noise. These fluctuations were found in the past in unannealed or inhomogeneous specimens.[26] The fluctuations were then accompanied by steps in the resistance transition. We have assumed that they are not significant since no voltage steps were found in the transition and the material was well annealed.

(4) A distribution of pulse length may also be caused by a size distribution of moving domains. An elongated normal domain generates a longer voltage pulse than a small domain. This effect gives rise to a lower cut-off frequency for the noise than flux flow by small domains.

(5) Flicker noise due to temperature fluctuations (as discussed in Ref. 20) was found above and below the helium λ point and had power spectra very similar to those measured on vanadium foils. It is, therefore, not discussed here.

The noise measurements suggest that at low fields the intermediate state behaves as a type-II superconductor. There is some pinning, and most of the flux is flowing either in bundles or as single flux tubes under the influence of a Lorentz force, generating a flux-flow voltage. When the field is increased, the normal regions grow and some of them may extend across the superconductor, thereby becoming immobile, so that the transport current causes an ohmic-loss voltage in these regions. The still moving domains interact with the immobile regions giving rise to a jerky flux motion.

At high fields most of the flux is contained in immobile normal regions and very few big domains are still moving.

Because of the complexity of the problem, the results of the noise measurements give only semiquantitative information on the flux-flow process. If noise measurements are combined with simultaneous microscopic observations of the structure, it may be possible to derive theoretical power spectra with more realistic assumptions than are used in this paper. This would then also allow a more exact determination of the flux-flow voltage.

The generation of the big normal domains during flux flow was assumed to be random. The process by which these domains are generated is not clear. Perhaps small flux units are formed at certain nucleation sites,[16,27] combining to bigger domains after nucleation.

Measurement of the noise spectrum on a current-carrying cylindrical wire in zero field would give information on the motion of vortex rings.

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[26] D. C. Baird, Can. J. Phys. **37**, 1292 (1959).

[27] D. C. Baird, Can. J. Phys. **42**, 168 (1959).