Even Hall effect in superconducting phase of $YBa_2Cu_3O_{7-\delta}$

Ya. V. Kopelevich, V. V. Lemanov, É. B. Sonin, and A. L. Kholkin
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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An even "Hall effect" has been observed in the superconducting phase of ceramic $YBa_2Cu_3O_{7-\delta}$. The effect is explained on the basis of a "directed motion" of vortices. A physical picture of the flow of a current above the critical value is drawn.

The Hall effect in the superconducting state of the high-T_c superconductors is now coming under study.[1–3] In taking up this problem ourselves, we have encountered an effect which indicates that the voltage transverse with respect to the current in these materials cannot be explained on the basis of the usual understanding of the Hall effect. The most important distinguishing feature of our observation is the existence of a transverse voltage which does not change sign upon a change in the sign of the external magnetic field. This behavior was established through measurements of the Hall voltage by the procedure proposed in Ref. 4 for measuring the anomalous Hall effect. In this procedure, the nonequipotential voltage is eliminated through a cyclic permutation of pairs of contacts instead of a change in the sign of the external magnetic field.

The samples which we studied had a superconducting transition temperature $T_c = 90$ K and various critical current densities j_c (1 A/cm^2, 10 A/cm^2, and 100 A/cm^2 at 77 K in the geomagnetic field). Measurements were carried out in magnetic

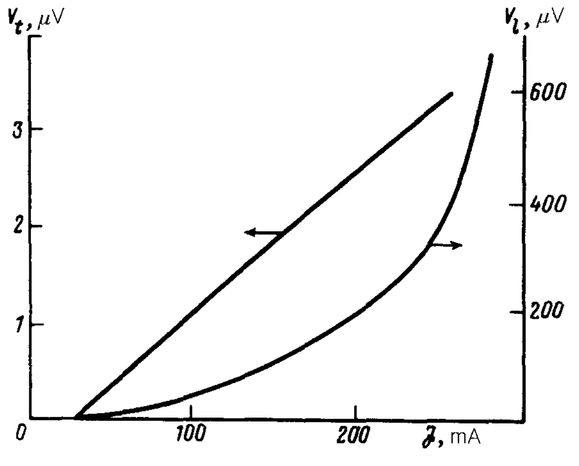

FIG. 1. The longitudinal voltage V_l and the transverse voltage V_t versus the current.

fields up to 10 kOe and at currents up to 500 mA at 77 K. The samples were plates with dimensions of $6\times6\times1$ mm with four point contacts, positioned symmetrically at the ends of the plate.

Figure 1 shows the longitudinal (V_l) and transverse (V_t) voltage components versus the current in a magnetic field of 50 Oe for a ceramic with $j_c = 1$ A/cm^2. From these data we find $V_l \sim J^{1.9}$ and $V_t \sim J^{0.95}$, i.e., $V_t \sim (V_l)^{1/2}$. The behavior of V_l and V_t as functions of the current at other values of the external magnetic field, and for samples with other values of j_c, is qualitatively the same as that shown in Fig. 1. When the temperature was lowered below T_c in magnetic fields of different polarities, the sign of V_t was established in a random way. We noted that when the sign of the external magnetic field was subsequently changed, the sign of V_t remained the same. We also observed a slow and aperiodic time evolution of the magnitude and sign of V_t in weak magnetic fields ($H < 400$ Oe). The shortest period for the ceramic with $j_c = 100\, A/\text{cm}^2$ was 2–3 h. For the ceramic with $j_c = 1$ A/cm^2 this period decreased to 30–40 min [the time required for the measurement of the $V_t(J)$ curve in Fig. 1 was 1–2 min]. In strong magnetic fields ($H > 400$ Oe), V_t did not vary with the time.

These results can be understood on the basis of a "directed motion" of vortices, a topic which in fact arose in research on classical superconductors.[5] It is assumed that a pinning force limits the motion of vortices in only one direction, forcing them to move along certain "channels." These channels might be weak links: grain boundaries and/or twin boundaries. Let us assume that a channel makes an angle α with the current $\mathbf{j}$ (Fig. 2). The balance of forces acting on a vortex can be described by[6]

$$\frac{[\mathbf{j}\times\vec{\Phi}_0]}{c} = -\eta\mathbf{u}_\Phi - \eta_\perp[\mathbf{u}_\Phi \times \vec{\Phi}_0] - \mathbf{F}_p\ , \qquad (1)$$

where $\vec{\Phi}_0$ is a vector whose absolute value is equal to the flux quantum $\Phi_0 = hc/2e$, which is directed along the magnetic field; $\mathbf{u}_\Phi$ is the velocity of the vortex; and $\mathbf{F}_p$ is the pinning force, which is directed perpendicular to the channel. To find the magni-

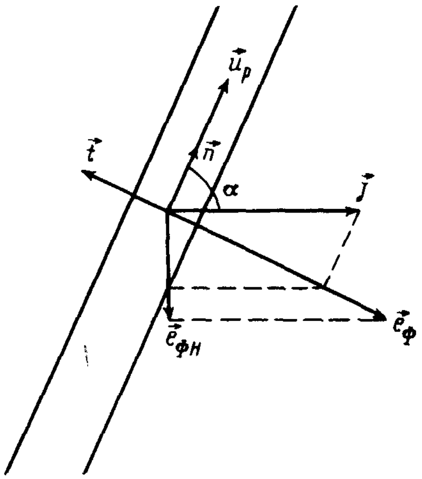

FIG. 2 Current and field in the resistive state of a superconductor with a directed motion of vortices.

tude of the velocity u_Φ during the directed motion, we need to project the equation of motion on to the **n** axis (the unit vector **n** runs along the channel). As a result, F_p drops out of the equation:

$$\frac{\mathbf{n}[\mathbf{j}\times\vec{\Phi}_0]}{c}=-\eta(\mathbf{u}_\Phi\mathbf{n})-\eta_\perp([\mathbf{u}_\Phi\times\vec{\Phi}_0]\mathbf{n}) . \tag{2}$$

The last term in (2) vanishes since we have $\mathbf{u}_\Phi=(\mathbf{u}_\Phi\mathbf{n})\mathbf{n}$, $(\mathbf{u}_\Phi\mathbf{t})=0$, where $\mathbf{t}=1/\Phi_0[\Phi_0\times\mathbf{n}]$ is a unit vector oriented normal to channel.

Hence,

$$u_\Phi=(\mathbf{u}_\Phi\mathbf{n})=-\frac{\Phi_0}{c\eta}\mathbf{j}\mathbf{t} . \tag{3}$$

The contribution to the electric field from one vortex is then

$$\mathbf{l}_\Phi=-\frac{1}{c}[\mathbf{u}_\Phi\times\vec{\Phi}_0]=\frac{\Phi_0}{c^2\eta}(\mathbf{j}\mathbf{t})\mathbf{t} . \tag{4}$$

The sign of the transverse electric field, like that of the longitudinal electric field, obviously remains the same when the sign of the magnetic field is changed. It follows from (4) that the field component perpendicular to the current (the "Hall" component) is proportional to $\sin 2\alpha$, i.e., is of varying sign. If the channels are oriented in a random fashion with respect to the current, the transverse field is a random quantity.

The following physical picture might be drawn of the flow of a current slightly above the critical value (the initial region of the current-voltage characteristic, before the onset of the linear asymptotic region; Fig. 1). Different current values are required to detach vortices from pinning centers in different regions of a sample. The critical current is the current at which the regions of depinned vortices form an infinite perco-

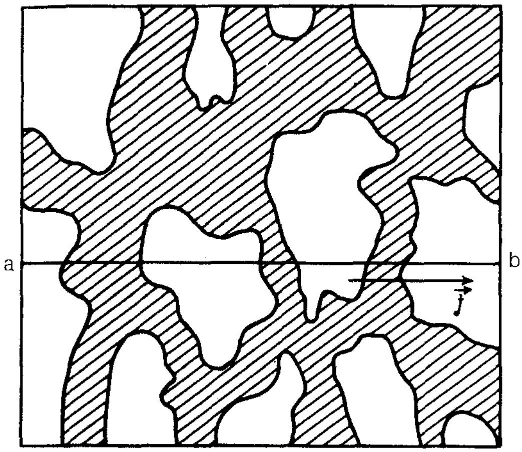

FIG. 3. Percolation cluster for vortices (the hatching). The "linear size" of the cluster is to be understood as that part of line *ab* which lies within the cluster.

lation cluster (Fig. 3), so that a vortex can traverse the cross section of the sample along this cluster. Although this cluster does grow with the current, it does not fill the entire volume of the sample. This growth process corresponds to a nonlinear growth of the longitudinal voltage with increasing current. The longitudinal voltage may be thought of as proportional to the "linear size" of a cluster, i.e., to that part of a line through the sample which lies inside the cluster. Since the transverse voltage is a random quantity, however, it must increase in proportion to the square root of the same quantity. It follows that the law $V_t \sim (V_l)^{1/2}$ should hold as the current is raised. This is the behavior observed experimentally. Further evidence for a random nature of the even "Hall effect" is the change in its magnitude and sign as time elapses, although the actual reason for this time variation of the parameters of the medium is not clear at this point. There is the possibility that the shape and position of the percolation cluster change, while the configuration and parameters of the weak links—the channels—remain the same. The situation might be compared with drifting ice in a river: The relief of the river remains unchanged, but ice jams can form in different places in the river. Two key points in our explanation of the phenomenon are the anisotropy of the resistance due to the motion of vortices along channels and the random nature of the spatial distribution of this anisotropy. The latter point in particular should be stressed, since if the anisotropic resistance tensor were spatially uniform, then our observation method could not have revealed the corresponding component.

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