LT 21 Proceedings of the 21st International Conference on Low Temperature Physics
Prague, August 8-14, 1996
Part S3 - Superconductivity 2: HTS - Vortices (theory)

Long-range attraction between a distorted vortex and the sample surface

Ernst Helmut Brandt[a], Roman G. Mints[b], and Igor B. Snapiro[b]

[a] Institut für Physik, Max-Planck-Institut für Metallforschung, D-70506 Stuttgart, Germany

[b] School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel

It is shown that in extremely anisotropic layered superconductors there is a long-range attraction between the sample surface and a randomly distorted vortex line parallel to the surface and to the c-axis. In the presence of strong random pinning, this long-range force attracts a distorted vortex line to the surface and may lead to flux creep towards the surface. The same interaction with the surface enhances the thermal fluctuations to depths much larger than the in-plane London penetration depth and might affect melting of the vortex lattice and evaporation of a vortex line into independent pancake vortices.

1. INTRODUCTION

Abrikosov vortex lines in layered superconductors have several unusual properties as compared to vortex lines in isotropic superconductors. In particular, vortex lines oriented perpendicular to the superconducting layers may be considered as a stack of two-dimensional point vortices or pancakes [1, 2, 3]. In the case of large anisotropy the pancakes interact via a magnetic pair-potential, which parallel to the layers decreases logarithmically and perpendicular to the layers decreases exponentially.

The interaction of pancakes within the same layer is repulsive while between different layers it is attractive and reduced by a factor $s/2\lambda \ll 1$, where s is the layer spacing and $\lambda = \lambda_{ab}$ is the penetration depth for the currents in the layers. As a consequence, the interaction of two straight stacks of pancakes is just the usual short-range repulsion of Abrikosov vortices. However, this short-range attraction applies only when the vortex line is perfectly straight. As soon as the vortex line is distorted, the compensation of repulsive and attractive terms in the vortex-vortex interaction is no longer ideal. As a consequence, randomly distorted vortex lines feel a long-range attraction to the surface. In this paper we consider this long-range attraction.

2. LONG-RANGE INTERACTION

We first give a simple physical interpretation of the long-range fluctuation-induced attraction. Within the London theory the condition of zero perpendicular current through a planar specimen surface may be satisfied by adding the magnetic fields and currents of image vortex lines [4]. Each vortex then is attracted to its image since the images have opposite orientation (antivortices).

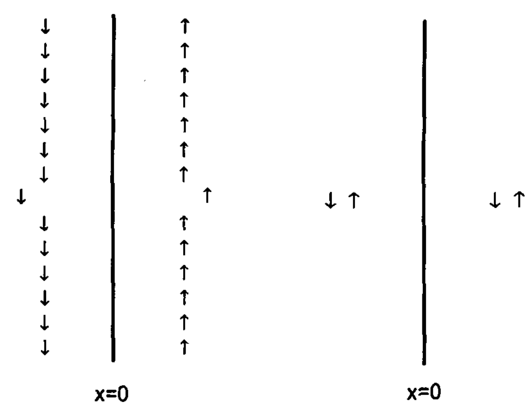

Figure 1: *Left:* A distorted vortex line and its image composed of pancakes (↑) and antipancakes (↓). *Right:* The two dipoles generated by the displacement cause a long-range attraction between the distorted vortex and the surface ($x = 0$).

Assume now that only one of the pancakes of a straight stack is displaced by a small distance u away from the surface. This local distortion is formally described by adding a pancake at the new position

$x+u$ and an antipancake at the equilibrium position x, which annihilates the original pancake. The same procedure has to be done with the image stack situated at the position $-x$ if the surface is at $x = 0$ (see Fig. 1). The two pancake-antipancake pairs are dipoles with a strength proportional to the displacement u and a dipole–dipole interaction energy proportional to u^2/x^2, where $1/x^2$ is the second derivative of the pancake-pancake potential ($\ln x$). Therefore, the distorted vortex line is attracted to its image, and thus to the planar surface, by a long-range potential proportional to u^2/x^2. This long-range interaction is in addition to the short-range interaction of a perfectly straight vortex with its image.

The interaction of a distorted vortex line with its image may be calculated from the interaction of pancakes [5]. For a distorted vortex line parallel to the surface $x = 0$ we define pancake displacements $\mathbf{u}_m = \mathbf{u}_m(z_m) = (u_{xm}, u_{ym})$ by writing $x_m = x + u_{xm}$ and $y_m = u_{ym}$. We first consider random and isotropic displacements with ensemble averages $\langle u_{xm}\rangle = \langle u_{ym}\rangle = 0$, $\langle u_{xm}u_{xn}\rangle = \langle u_{ym}u_{yn}\rangle = f(|m-n|)$, $\langle u_{xm}u_{yn}\rangle = 0$. The long-range interaction energy with the image line for $2x \gg \lambda$ then becomes equal to

$$E_{\text{int}} = -\frac{\Phi_0^2 L}{32\pi\mu_0\lambda^3 x^2}\int_0^\infty dz\,\exp\Bigl(-\frac{z}{\lambda}\Bigr)\,g(z), \qquad (1)$$

where $g(z)$ is the correlation function

$$g(z) = \langle[\mathbf{u}(z) - \mathbf{u}(0)]^2\rangle\,. \qquad (2)$$

At the same time the linear elastic self-energy of a distorted vortex line takes the form

$$E_{\text{self}} = \frac{\Phi_0^2 L}{8\pi\mu_0\lambda^4}\int_0^\infty dz\,\exp\Bigl(-\frac{z}{\lambda}\Bigr)\,\frac{g(z)}{z}. \qquad (3)$$

The similarity of Eqs. (1) and (3) leads to the following useful relationship. If the correlation function Eq. (2) increases algebraically, *i.e.*, $g(z) = \text{const}\cdot|z|^\gamma$, one has (still for $2x \gg \lambda$),

$$E_{\text{int}} = -(\gamma\lambda^2/4x^2)\,E_{\text{self}}\,. \qquad (4)$$

Therefore, in general the interaction energy is not a very small correction to the elastic energy.

Large fluctuations and local tilt of flux lines can be caused by pinning. Random pinning forces on a single flux line would cause square displacements diverging proportional to the number of forces. More realistic random pinning *potentials* lead to finite vortex displacements. For a crude estimate assume that random pins of density n_p are so strong that the vortex line wanders an average distance squared of order $(4n_p s)^{-1}$ as it passes to the next layer. This yields $g(z) \approx z/(n_p s^2)$, and the interaction energy with the surface is described by Eq. (4) with $\gamma = 1$. The resulting long-range force $-dE_{\text{int}}/dx$ in principle may drive the vortex line to the surface.

In the case of thermal fluctuations Eqs. (1) and (3) result in

$$\frac{\langle\mathbf{u}^2\rangle}{\lambda^2} \approx \frac{8\pi\mu_0\lambda^2 k_B T}{s\Phi_0^2\ln(\alpha\lambda/s)}\left[1 + \frac{\lambda^2}{4x^2}\,\frac{1}{\ln(\alpha\lambda/s)}\right], \qquad (5)$$

where the numerical factor $\alpha \sim 1$. Thus the correction to the thermal fluctuations arising due to the long-range interaction decreases away from the surface only as a power law. This increase of $\langle\mathbf{u}^2\rangle$, which in the total energy exactly compensates the spatial dependence of the term E_{int}, originates from the softening of the flux-line lattice near the surface.

3. CONCLUSIONS

In conclusion, we have shown that in extremely anisotropic layered superconductors there is a long-range interaction between the sample surface and a distorted vortex line parallel to the surface and to the c-axis. This interaction causes a spatial variation of the thermal fluctuations even at distances much larger than the in-plane London penetration depth, which might affect the melting process of the vortex lattice [6] and the evaporation of vortex lines into independent pancake vortices [3, 7]. In the presence of sufficiently strong random pinning, a fluctuation-induced long-range force attracts the distorted vortex line to the surface. This additional force means a bulk current density far inside the superconductor and may lead to flux creep towards the surface.

We acknowledge support from the German-Israeli Foundation for Research and Development, Grant # 1-300-101.07/93.

REFERENCES

[1] K.B. Efetov, Zh. Eksp. Teor. Fiz. **76** 1781 (1979).
[2] S.N. Artemenko and A.N. Kruglov, Phys. Lett. A **143**, 485 (1990).
[3] J.R. Clem, Phys. Rev. B**43** 7837 (1991).
[4] C.P. Bean and J.D. Livingston, Phys. Rev. Lett.**12**, 14 (1964).
[5] M.V. Feigel'man, V.B. Geshkenbein, and A.I. Larkin, Physica C **167**, 177 (1990).
[6] D.R. Nelson, Phys. Rev. Lett.**60**, 1973 (1988);
[7] L.N. Bulaevskii, S.V. Meshkov and D. Feinberg, Phys. Rev. B**43**, 3728 (1991).