Metastable vortex structures in a $Bi_2Sr_2CaCu_2O_x$ plate

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Two stable vortex structures can coexist in $Bi_2Sr_2CaCu_2O_x$ plates, which have an exceedingly pronounced crystalline anisotropy. One configuration is a slightly hexagonal lattice; the other is a configuration of vortex chains. These metastable structures coexist at small values of the induction ($B<20$ G) in a sufficiently thick plate ($d>20\lambda_a$).

Abrikosov vortices in thick superconducting plates (with a thickness d much greater than the magnetic penetration depth λ) have several distinctive features.[1] An isolated vortex in an in-plane magnetic field is always curved. The ends of a vortex emerging at external surfaces are oriented strictly normal to the plate surface, n, while the central part of a vortex deviates from n by a constant angle toward the in-plane field H_2. In a uniaxial superconductor with an anisotropy axis parallel to n, the central segment of a vortex lies a distance on the order of $\lambda_a \mu_a^{-1}$ from the plate surface ($\lambda_a = \lambda \mu_a^{1/2}$, where μ_a is an anisotropy parameter of the superconductor). The linear tension in a vortex causes it to bend smoothly near a surface. With increasing H_2, the curvature of the vortex becomes more pronounced, and the length of the vortex increases.

Segments of vortices near a surface interact with each other primarily through the volume around the superconductor. The long-range repulsion falls off as $1/R$ and is independent of the anisotropy. The interaction of the central segments of vortices is essentially the same as the short-range interaction of vortices in an unbounded superconductor.[2,3] It depends on the inclination of the vortex thread and on the anisotropy μ_a. The primary distinguishing feature is that the interaction in a plate depends on the shape of the vortices, whose length increases with H_2. In unbounded superconductors with $\mu_a<1$, vortices can attract each other, forming vortex chains.[2] The vortex–vortex attraction lowers the total energy of the vortex chain, with the result that two types of chains can coexist under the condition $\mu_a<0.28$. At a fixed direction of the external field, these two types differ in the inclination of the vortices and in the distances between vortices in the chain. Chains of different types can coexist only if the external field **H** is parallel to the anisotropy axis within 0.1°.

It is impossible to predict a corresponding effect in plates of finite thickness, since some new factors have to be taken into account: The vortices in a plate are curved, their length may change, and there is a long-range repulsion between vortices. The long-range interaction prevents vortices from forming isolated chains, and it aligns them in a sparse hexagonal structure. As the in-plane field is strengthened, however, the central segments of vortices attract each other and become longer. This effect

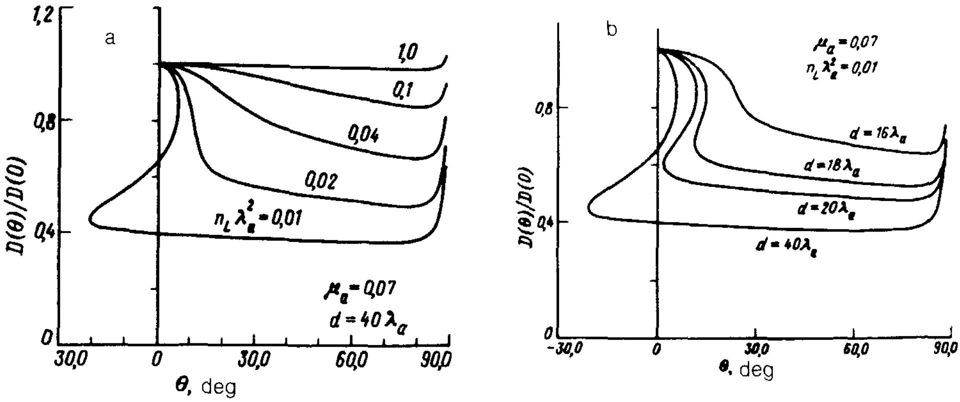

FIG. 1. The distance between vortices in a chain, D, versus the inclination (θ) of the external field **H**. a—Calculated behavior for a plate of thickness $d=40\lambda_a$ and for various values of the induction $n_L\lambda_a^2$; b—for plates of various thicknesses d at a fixed induction $n_L\lambda_a^2=0.01$.

intensifies the attraction between vortices and may lower the total energy of the vortex structure.

In an effort to observe metastable vortex structures, we studied a thick ($d\gg\lambda_a$) plate of a $Bi_2Sr_2CaCu_2O_x$ (BSCCO) single crystal with anisotropy axis running along the normal n. In an oblique magnetic field $\mathbf{H}=nB+\mathbf{H}_2$ the vortex concentration is fixed at $n_L=B/\phi_0$, and the vortex structure can be described completely by the parameters D and κ_2, where κ_2 is the tangent of the angle between $\mathbf{H}_2$ and the central part of the vortex, and D is the distance between vortices in the lattice, measured at the surface of the plate along the direction of $\mathbf{H}_2$. We found the parameters D and κ_2 through a numerical solution of the corresponding equilibrium equations.

Figure 1 shows the equilibrium parameter D versus the inclination of the external field, $\theta=\arctan(H_2/B)$. These results clearly demonstrate the existence of a hysteresis during magnetization of the superconducting plate. In the angular interval $|\theta|<20°$, three equilibrium structures, differing in D and κ_2, can exist. The stability of these solutions is determined by the sign of the two elastic moduli describing the deformation of the inclination of the vortices toward the field $\mathbf{H}_2$ (the modulus T_{22}) and in the perpendicular direction (T_{11}). The inclination moduli are expressed in terms of the equilibrium $\kappa_2(H_2)$ dependence and are given by

$$T_{11}=\frac{BH_2}{4\pi}\frac{1+\kappa_2^2}{\kappa_2}, \quad (1)$$

$$T_{22}\simeq\frac{B}{4\pi}\frac{\partial H_2}{\partial\kappa_2}. \quad (2)$$

It can be seen from (1) that the stable vortex structures in Fig. 1 lie to the right of the ordinate axis ($\theta=0$) and that the vortices are tilted toward $\mathbf{H}_2$. It follows from (2) that only solutions with a $\kappa_2(H_2)$ curve of positive slope are stable. A calculation of

$\kappa_2(H_2)$ shows that two extreme branches of $D(H_2)$ are stable in the hysteresis region: the upper and lower branches. The central branch is always unstable.

Let us look at the results.

1. One of the metastable vortex structures is a slightly deformed hexagonal lattice with $D(\theta) \sim D(0)$, and the other is a structure of vortex chains. The distance between vortices in a chain, $D(\theta)$, is much smaller than the distance between chains, $D^2(0)/D(\theta)$.

2. Metastable structures exist at small values of the induction, $B < 0.02\phi_0\lambda_a^{-2} \sim 2H_{c1}$. For BSCCO with $\lambda_2 = 0.15$ μm, these induction values are $B < 20$ G. As the induction is raised (Fig. 1a), the hysteresis region shifts toward larger angles θ, while the width of this region decreases. There are certain critical values of the induction at which the hysteresis disappears; these critical values depend on the plate thickness.

3. The effect is very sensitive to the plate thickness (Fig. 1b). At a fixed induction, the hysteresis region shrinks with the thickness d. There exists a critical thickness $d \sim 2\lambda_a\mu_a^{-2}$, below which metastable structures are not observed.

4. In an unbounded BSCCO single crystal, a hysteresis is observed at $\theta < 0.01°$, while in a plate it exists at $\theta < 20°$. From these results we find a qualitative description of the metastable vortex structures which have been observed[4] at the surface of a BSCCO single crystal. When the field **H** deviates from the normal n, the induction B decreases, and the in-plane field H_2 increases. The hexagonal vortex lattice is deformed very slightly. At the critical inclination angle θ_{cr} one more stable structure—a chain of vortices—arises. The value of θ_{cr} depends strongly on the vortex concentration $n_L\lambda_a^2$. It may be that the difference between the parameters λ_a and d in Ref. 5 made it impossible to observe metastable structures in $Tl_2Ba_2CaCu_2O_x$ crystals at the same values of H as in Ref. 4.

There is a significant difference between the observed[4] value $\theta_{cr} \sim 60°$ and our prediction $\theta_{cr} \sim 20°$. One possible reason for this discrepancy is that the interaction near the surface in layered crystals is stronger than in an anisotropic London superconductor. The correspondence between unbounded layered and London superconductors was demonstrated in Ref. 6. The effect of the free surface requires further research.

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