N92-21632

ELLIPTICAL FLUX VORTICES IN $YBa_2Cu_3O_7$

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Abstract- The most energetically favorable vortex in $YBa_2Cu_3O_7$ forms perpendicular to an anisotropic plane. This vortex is elliptical in shape and is distinguished by an effective interchange of London penetration depths from one axis of the ellipse to the other. By generalizing qualitatively from the isotropic to the anisotropic case, we suggest that the flux flow resistivity for a vortex that forms perpendicular to an anisotropic plane should have a preferred direction. Similar reasoning indicates that the Kosterlitz-Thouless transition temperature for a vortex mediated transition should be lower if the vortex is elliptical in shape.

Introduction

The free energy per unit length of an isolated Abrikosov vortex in a type II superconductor is given by [1]

$$\epsilon_1 = \frac{H_{c1}\Phi_o}{4\pi}, \tag{1}$$

where H_{c1} represents the lower critical field and Φ_o represents a single flux quantum. Single crystal $YBa_2Cu_3O_7$ can be viewed as a type II superconductor that contains one plane in which the superconducting properties are isotropic (*ab* plane) and two planes in which the superconducting properties are equivalently anisotropic (*ac* and *bc*). If ϵ_1^{ab} represents the free energy associated with a vortex that forms perpendicular to the isotropic plane, and $\epsilon_1^{ac} = \epsilon_1^{bc}$ represents the free energy associated with a vortex that forms perpendicular to an anisotropic plane, then for $YBa_2Cu_3O_7$ [2]

$$\frac{\epsilon_1^{ac}}{\epsilon_1^{ab}} = \frac{H_{c1}^{ac}}{H_{c1}^{ab}} = \frac{0.05T}{0.5T} = 0.1. \tag{2}$$

Equation (2) indicates that the formation of a vortex perpendicular to the anisotropic plane requires only 1/10 of the energy required by the formation of a vortex perpendicular to the isotropic plane.

But in order for a vortex to form perpendicular to an anisotropic plane, the anisotropic plane has to be incident on a non-superconducting region. This is certainly the case in an *a* (or *b*) axis oriented thin film, where almost the entire surface is an anisotropic plane. Further, for bulk $YBa_2Cu_3O_7$, studies indicate that as many as 75 % of the grain boundaries in a "shake and bake" sample contain *ab* planes [3], while, depending on the density, 18 to 35 % of the bulk sample consists of empty pockets or voids [4]. If many of the isotropic *ab* planes are incident on other grains, then many of the anisotropic *ac* and *bc* planes should be incident on the voids. Evidently there is ample opportunity for the formation of vortices perpendicular to anisotropic planes, even inside bulk $YBa_2Cu_3O_7$.

Discussion

The London theory solution for the magnetic flux density around a vortex that forms perpendicular to an isotropic plane indicates that [5]

$$B \propto K_o\left(\frac{r}{\lambda}\right), \tag{3}$$

where r is the cylindrical coordinate, λ is the London penetration depth, and K_o is a modified Bessel function of the second kind. The London theory solution for the magnetic flux density around a vortex that forms perpendicular to an anisotropic plane indicates that [6,7]

$$B \propto K_o\left(\sqrt{\left(\frac{x}{\lambda_{yy}}\right)^2 + \left(\frac{y}{\lambda_{xx}}\right)^2}\right), \tag{4}$$

where B is z-directed and λ_{yy}, λ_{xx} are the London penetration depths in the y and x directions.

Apart from the fact that the contour lines are elliptical in shape, the most interesting aspect of equation (4) is that it predicts an effective interchange of penetration depths around the vortex. In $YBa_2Cu_3O_7$ for example, measurements by Worthington *et al.* reveal that the longest penetration depth is in the *c* direction while the longest coherence length is in the *a* (or *b*) direction [2]. These data should lead to a "cat's eye" vortex model as shown in Figure 1a. (Here x is identified with the *c* direction while y could be either the *a* or the *b* direction.) The orientation of penetration depths ought to demand that $B(0, \lambda_{yy}) = B(\lambda_{xx}, 0)$. Instead as shown in Figure 1b, equation (4) predicts that $B(0, \lambda_{xx}) = B(\lambda_{yy}, 0)$. This remarkable shift has actually been observed by Dolan *et al.*, who report oval vortices with penetration depths that are shortest in the *c* direction [8].

The fact that the most energetically favorable vortex in

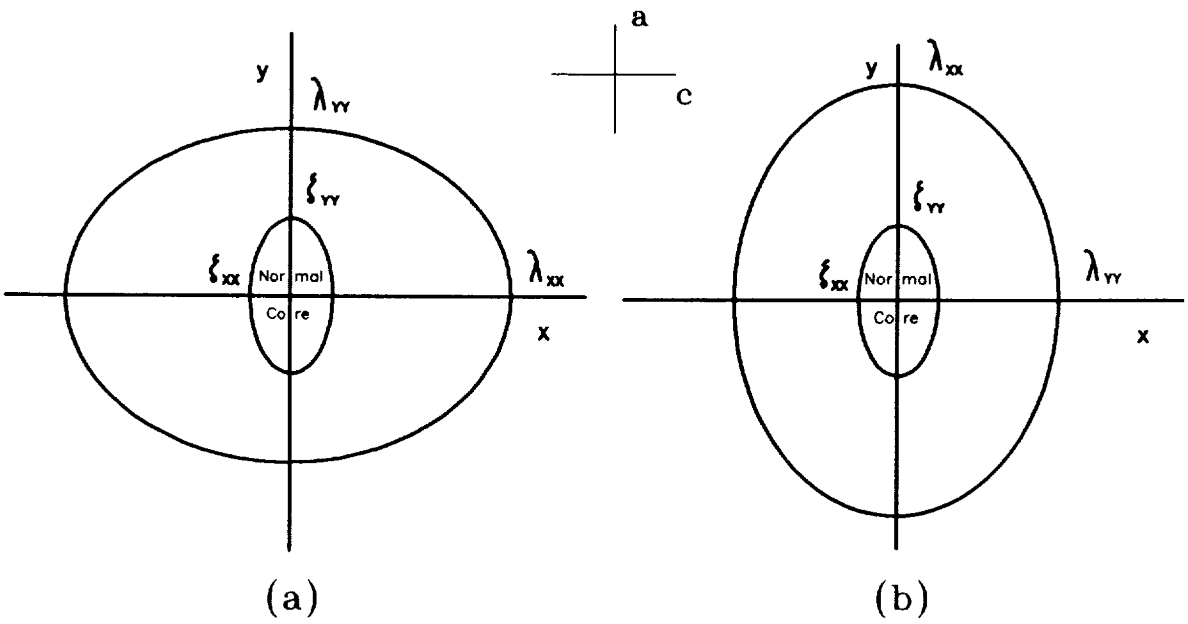

Figure 1 An Abrikosov Vortex in the Anisotropic Plane of $YBa_2Cu_3O_7$
(a) Anticipated Structure Based on Measurements of H_{c1}
(b) Actual Structure Based on London Theory and Observation

$YBa_2Cu_3O_7$ forms perpendicular to an anisotropic plane and is elliptical in shape, ought to have important physical consequences. By way of suggesting directions for future study, we now examine two expressions that were derived from isotropic considerations, and, in lieu of presenting a rigorous anisotropic treatment, we will *qualitatively* extend these equations to the anisotropic case.

Working from the Bardeen-Stephen model, Tinkham gives the following expression for flux flow resistivity in an isotropic superconductor [9]

$$\rho_f \propto \rho_n \left(\frac{B}{H_{c2}}\right), \tag{5}$$

where ρ_n is the normal state resistivity, B is the space averaged magnetic flux, and H_{c2} is the upper critical field. For $YBa_2Cu_3O_7$, ρ_n along c is large compared to ρ_n along a (or b) [10], while H_{c2} along c is small compared to H_{c2} along a (or b) [2]. Applied to (5), these differences lead to

$$\rho_{f_c} > \rho_{f_a} = \rho_{f_b}. \tag{6}$$

Equation (6) indicates that the flux flow resistivity in the a (or b) direction is less than the flux flow resistivity in the c direction. Equation (4) indicates that the vortex is elongated in the a (or b) direction. Evidently, under the influence of a driving force, the vortex will move most easily in the direction of its own elongation. This prediction appears compatible with an argument given by Clem, in which the entropy flow from the trailing to the leading edge of a moving vortex results in dissipation [11]. An elliptical vortex should create the least amount of entropy flow (and hence the least dissipation) when it moves in the direction of its own elongation.

The phase transition of an ultra thin superconducting film is another phenomenon that might be affected by the formation of elliptical vortices. For an isotropic thin film, the Kosterlitz-Thouless transition temperature, T_{KT}, is given by [12]

$$k_B T_{KT} = \frac{\Phi_o^2}{32\pi^2}\frac{d}{\lambda^2}, \tag{7}$$

where d is the film thickness, and λ is the bulk penetration depth. In a c-axis oriented thin film, $\lambda = \lambda_a = \lambda_b$. For an a (or b) axis oriented film, it seems appropriate to replace $1/\lambda^2$ by an effective value. For example,

$$\left(\frac{1}{\lambda^2}\right)_{effective} \approx \frac{1}{2}\left[\frac{1}{\lambda_a^2} + \frac{1}{\lambda_c^2}\right]. \tag{8}$$

Since $\lambda_c > \lambda_a$, one concludes that

$$(T_{KT})_{\text{a axis oriented}} < (T_{KT})_{\text{c axis oriented}}.$$

If a vortex mediated KT transition does in fact take place in high T_c superconducting thin films, then the above argument suggests that the transition region in an a-axis oriented thin film would be wider than the transition region in a *c*-axis oriented thin film.

Conclusion

The fact that the most energetically favorable vortex in $YBa_2Cu_3O_7$ is elliptical in shape should have important physical consequences. By qualitatively generalizing from the isotropic to the anisotropic case, we note for example, that both the Kosterlitz-Thouless transition temperature and the flux flow resistivity could be affected by vortex shape.

Acknowledgement

This work was partially supported by DARPA grant no. MDA972-88-J-1006.

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