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LETTER TO THE EDITOR

Flux-lattice melting in an anisotropic superconductor: limit of decoupled layers

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Abstract. The Lindemann criterion for flux-lattice melting is extended to the limit of electronically decoupled layers (infinite effective mass perpendicular to the layers). The resulting melting temperature resembles the formula for two-dimensional melting in a film, but with an effective film thickness characteristic of electromagnetic interlayer coupling.

Recent experiments by Gammel *et al* [1] suggested that in a strong magnetic field the flux lattice in a high-T_c Bi- or Tl-based superconductor can melt at a temperature much less than $T_c(B)$. Stimulated by this, there have been a number of recent calculations of the Lindemann criterion for melting of the flux lattice [2–6]. These calculations are in general agreement that at high fields, the motion of the vortices can decouple from the motion of the field, leading to very deformable flux lattices and a low melting temperature, T_M. A calculation which includes the large effective mass anisotropy leads to the conclusion that the low values of T_M are directly caused by the large value of the effective Ginzburg–Landau parameter, κ_{eff}. In turn, κ_{eff} is so large because of the weakness of interlayer coupling: $\kappa_\perp^2 \sim m_\perp$, where $m_\perp$ is the electronic effective mass perpendicular to the conducting CuO_2 planes in these materials.

It is the purpose of this letter to point out that the expression for the Lindemann criterion derived in [6] remains valid in the limit of electronically decoupled layers, $m_\perp \to \infty$. In this limit, the root mean square vortex line displacement u becomes:

$$u^2/a^2 = (24\pi\kappa_\parallel^2\beta_0 B/\Phi_0^3 H_c^2)^{1/2} k_B T \tag{1}$$

where a is the flux-lattice constant, Φ_0 is the flux quantum, $\kappa_\parallel$ is the in-plane Ginzburg–Landau parameter, and H_c is the thermodynamic critical field. Melting is assumed to occur when u reaches a definite fraction of the flux line spacing, typically $u \simeq 0.1a$.

The above criterion bears a close resemblance to the criterion for the melting of a *two-dimensional* flux lattice (e.g., in a thin film of thickness d) [7, 8]:

$$k_B T_M = (a^2/4\pi)c_{66} d \tag{2}$$

where the shear modulus can be written as $c_{66} = \alpha H_c B/16\pi\kappa$, with α a constant of order unity. Equations (1) and (2) become identical, up to a multiplicative constant of order unity, if κ in (2) is identified with $\kappa_\parallel$, and d is replaced by

$$d_{eff} = \sqrt{\pi\Phi_0/B}. \tag{3}$$

Thus, in this limit, the flux lattice melts almost independently within each layer, but with a weak interlayer coupling which correlates the vortices over a distance $d_{eff} \simeq 80$ nm at $B = 1$ T. It should be noted that this fluxon coherence length agrees with one of the alternative choices ($d_{eff} \simeq a$) postulated by both Yeshurun and Malozemoff [9] and Tinkham [10] for the c axis coherence length of a flux bundle involved in an elementary flux jump. This interlayer coupling is presumably an electromagnetic effect, as in Giaever's DC transformer [11]. Thus, as the applied field H approaches H_{c1}, the internal magnetic field $B \rightarrow 0$, and $d_{eff} \rightarrow \infty$. This follows directly from Maxwell's equations: near H_{c1} all of the vortices are isolated, so their coherence length becomes that of an isolated tube of magnetic flux, which is infinite, since $\nabla \cdot \boldsymbol{B} = 0$.

This result has an important bearing on the question of pinning strength in these materials. It has been claimed that a three-dimensional flux lattice must be in the strong-pinning limit since each vortex will be pinned at at least one point along its length. However, if the vortices are only correlated over a distance d_{eff}, then the flux lattice should be in the *weak-pinning* limit if the separation between pinning sites is greater than d_{eff} in the direction perpendicular to the layers.

Note that, since the melting is fundamentally a phenomenon associated with a single layer, the transition should be at least as sharp as the ordinary Kosterlitz–Thouless transitions in thin films.

Finally, since the Lindemann criterion holds for fields either parallel or perpendicular to the c axis [6], (1) should also be valid when the field is applied parallel to the basal plane. The interpretation is less straightforward in this case, since there is no single-layer result similar to (2) with which it can be compared.

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