Thermal melting and order–disorder transition in high-T_c superconductors

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Abstract

In theoretical investigations of the H-T phase diagrams of type-II superconductors, one usually assumes that the influence of flux-line pinning on the melting line, and of the entropy term in the free energy on the order–disorder transition, may be disregarded. We analyze when this approximation is justified for high-T_c superconductors with various types of pinning.

Key words: H-T phase diagrams of high-T_c superconductors; melting of flux-line lattice; quenched disorder

In three-dimensional high-T_c superconductors with pinning, two phase transition lines are known to exist in the magnetic field H - temperature T plane: The line where a quasiordered Bragg glass thermally melts into a flux-line liquid, and the order–disorder transition line separating the Bragg glass from an amorphous vortex state [1–4]. The melting is caused by thermal vibrations of the lattice, while the order–disorder transition is induced by quenched disorder in the vortex system. These two lines merge at some point in the H-T plane. Although both transitions are accompanied by a proliferation of dislocations in the vortex lattice, it was argued [5] that the dislocation density ρ is essentially different in these cases: $\rho \sim a^{-2}$ for melting, and $\rho \sim R_a^{-2}$ for the order–disorder transition. Here a is the spacing between flux lines, and R_a is the so-called positional correlation length [6] within which the relative vortex displacements caused by the quenched disorder are of the order of a. In fact, an intersection of these two different phase transition lines occurs in this scenario, and the order–disorder line terminates at the intersection point while the melting line continues for some distance to higher H. Recent experiments [7,8] for YBaCuO seem to support this scenario.

Phase diagrams of superconductors with pinning reflect the competition of three characteristic energies [3]: the elastic energy, the pinning energy, and the energy of thermal fluctuations. At melting, the cost in the elastic energy due to the proliferation of dislocations is mainly balanced by the entropy gain associated with thermal fluctuations, while the role of the pinning energy, as can be shown, is determined by the parameter a/R_c. Here R_c is the transverse collective pinning length [6]. On the other hand, at the order–disorder transition, the balance of pinning energy and elastic energy is most important, while the relative contribution of the entropy gain is negligible at low temperatures and, according to the scenario of Ref. 5, is determined by the ratio a/R_a near the intersection point. Thus, if the intersection of the melting and the order–disorder lines occurs sufficiently deep in the bundle pinning region (so that $R_c \gg a$ at this point), the scenario of Ref. 5 leads to the conclusion that one can find the melting line by neglecting the pinning, and the order–disorder line by neglecting the entropy gain. Just this approximation was used in our paper [4] (and, in fact, in Refs. 1-3) for analyzing the phase diagrams of superconductors. In this paper we investigate the conditions under which this approximation is really valid. In our analysis based on Ref.4, we determine the boundaries of different pinning regimes self-consistently, find the order–disorder line not only in the single vortex pinning regime (as did Refs. 1-3) but also in the bundle pinning regime, and calculate the intersection point $H_{dis}(T_i) = H_m(T_i)$.

We find the order–disorder line $H_{dis}(T)$ and the melting line $H_m(T)$ using the following two Lindemann criteria [4]: $u_T^2 = c_{Lm}^2 a^2$ for the melting, and $u(a,0)^2 = c_L^2 a^2$ for the order–disorder transition. Here u_T is the magnitude of the thermal fluctuations of vortices, and $u(a,0)$ is the mean relative displacement of neighboring flux lines caused by the quenched disorder. For simplicity, the Lindemann constants c_L and c_{Lm} below are assumed to be equal, $c_{Lm} = c_L$. If the displacement $u(a,0)$ is found by using results of the collective pinning theory [6], the phase diagrams of 3D superconductors are determined by only two parameters [4]: the Ginzburg number Gi, and a parameter describing the strength of the quenched disorder in the flux-line lattice, $D = \epsilon\xi(0)/L_c(0)$. Here ξ is the coherence length, L_c the Larkin pinning length in the single vortex pinning regime, both taken at $T = 0$, and ϵ is the anisotropy. The intersection point T_i of $H_{dis}(T)$ and $H_m(T)$ is mainly determined by the combination $\nu = (2\pi)^{3/2} D^3 / Gi^{1/2}$ [4].

We begin our analysis with the case of δT_c pinning [6] where $\xi(T)/L_c(T) \propto g_0(t) = (1-t^2)^{-1/6}$, $t = T/T_c$. When the parameter ν is of the order or less than unity, and hence the intersection point T_i is essentially below T_c, the ratio R_c/a calculated along the melting line is sufficiently large in the interval $T_i < T < T_c$, and only near T_i it decreases to several units. As to R_a/a near T_i, it is larger than R_c/a since one always has $R_a > R_c$. Thus, the above approximation is well justified, and only very close to the intersection point corrections can appear. The situation in the case $\nu > 1$ ($\nu \approx 4$) is shown in Fig. 1. It is seen that although the melting line lies in the bundle pinning region, R_c is large only near T_c, thus in a wide range of temperatures pinning may affect the melting line. This decrease of R_c/a is related to the fact that at large ν ($\nu > 8$ in the case $c_{Lm} = c_L = 0.25$) the melting line enters the lower single vortex pinning region near T_c.

In the case of the so-called δl pinning [6] where $g_0(t) = (1-t^2)^{1/2}$, the situation is similar to that of δT_c pinning with a small ν: At the intersection point T_i, the ratio R_c/a again is of the order of several units, but it sharply increases along the melting line with increasing T, Fig. 2. This fact is also evident from the position of the boundary $H_{lb}(T)$ separating the regions of small and large bundle pinning (where R_c equals the London penetration depth λ [6]). Thus a correction to the melting line is expected only near T_i. Interestingly, for both types of pinning, R_c/a at T_i is of the same order and only weakly depends on Gi and D. This probably means that at T_i the pinning energy always has reached some fraction of the elastic energy.

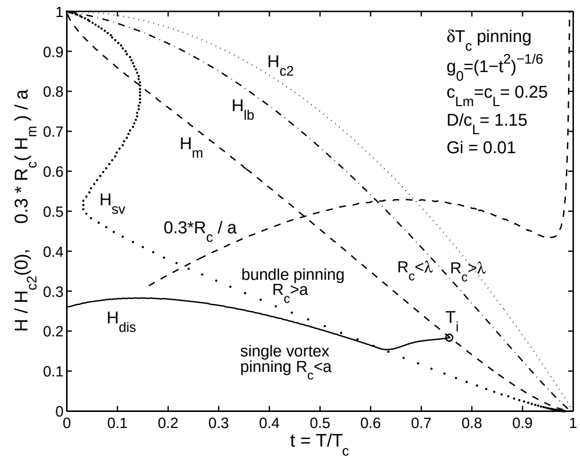

Fig. 1. The order–disorder line $H_{dis}(t)$ for the case of δT_c pinning, the melting line $H_m(t)$, the boundary of the single vortex pinning regime $H_{sv}(t)$, the boundary between the small and the large bundle pinning regimes $H_{lb}(t)$ (for $\kappa = \lambda/\xi = 100$), and the mean-field upper critical field $H_{c2} = H_{c2}(0)(1-t^2)$. The dependence of R_c/a *along the melting line* is also shown.

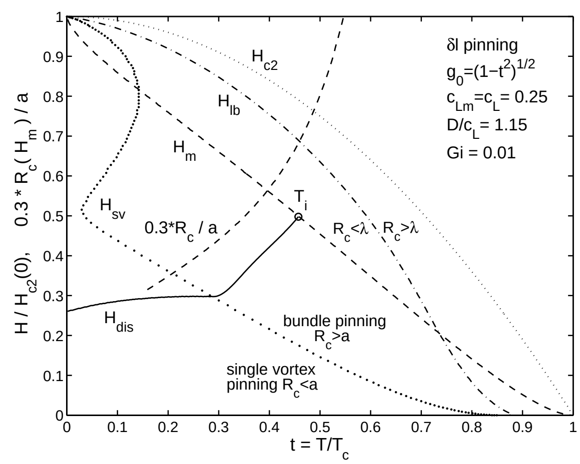

Fig. 2. As Fig. 1 but for the case of δl pinning.

References

[1] D. Ertaş, D.R. Nelson, Physica C **272** (1996) 79.

[2] T. Giamarchi, P. Le Doussal, Phys. Rev. B**55** (1997) 6577.

[3] V. Vinokur, B. Khaykovich, E. Zeldov, M. Konczykowski, R.A. Doyle, P.H. Kes, Physica C **295** (1998) 209.

[4] G. P. Mikitik, E. H. Brandt, Phys. Rev. B**64** (2001) 184514.

[5] J. Kierfeld, V. Vinokur, Phys. Rev. B**61** (2000) 14928.

[6] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. **66** (1994) 1125.

[7] D. Pal, S. Ramakrishnan, A.K. Glover, D. Dasgupta, B.K. Sarma, Phys. Rev. B**63** (2001) 132505.

[8] N. Kobayashi, T. Nishizaki, K. Shibata, T. Sato, M. Maki, T. Sasaki, Physica C **362** (2001) 121.