Unified Theory of Vortex Loops and Lines

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Abstract

A theory of fluctuations in type-II superconductors subjected to a weak magnetic field, **H**, is presented. The standard GL formulation is recast in terms of a new "superconducting" order parameter $\Phi(\mathbf{r})$, representing thermally-generated vortex loops, in an overall magnetic field equal to zero, consisting of **H** and a set of unit fluxes attached to N_Φ vortex lines. Pivotal role in the theory is played by a new transition line $T_\Phi(H)$, along which $\Phi(\mathbf{r})$ attains long range order. This phase transition arises through proliferation of infinite vortex loops in the background of field-induced vortex lines, and is a true finite field version of the zero-field 3D XY superconducting transition. At $T_\Phi(H)$ field-induced vortex lines loose their effective line tension relative to **H**. At zero field, $\Phi(\mathbf{r})$ and the familiar $\Psi(\mathbf{r})$ are equivalent, and the line tension of large loops, $\mathcal{T}$, and the helicity modulus, Υ, vanish simultaneously, at $T = T_{c0}$. For $\mathbf{H} \neq 0$, however, these two forms of "superconducting" order are not the same and the "superconducting" transition is split in two branches: Υ vanishes at $T_m(H)$ while $\mathcal{T}$ and associated Φ-order disappear only at $T_\Phi(H)$. I argue that $T_\Phi(H) > T_m(H)$ at lower fields and $T_\Phi(H) = T_m(H)$ for higher fields. Both Φ- and Ψ-order are present in the Abrikosov vortex lattice ($T < T_m(H)$) while both are absent in the true normal state ($T > T_\Phi(H)$). The intermediate Φ-ordered phase ($T_m(H) < T < T_\Phi(H)$) can be viewed as a "line liquid". Various experimental consequences of the theory are explored in detail. [Z. Tešanović, Phys. Rev. B **51**, 16204 (1995); cond-mat/9801306.]