“Mean-Field” Theory for Self-Induced Vortex Lattice in Ferromagnetic Superconductors

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A large family of magnetic superconductors such as UGe_2, URhGe and UCoGe were discovered in the last decades [1], although superconductivity and magnetism are mutually excluded according to the standard BCS theory. The upper critical field H_{c2} far beyond the Pauli limit, and large internal magnetic field accompanied with spontaneous magnetic moments suggest an equal-spin triplet-pairing (ESP) state [2,3]. The NQR/NMR studies in UCoGe have revealed that the longitudinal critical ferromagnetic fluctuations play an essential role [4,5], which favor the ESP state such as $\Delta_\sigma\varphi(\hat{\mathbf{k}})$ ($\varphi_\sigma \propto e^{i\sigma\phi}$, $\sigma = \pm 1$).

A remarkable feature of the ferromagnetic superconductivity is a self-induced vortex lattice [6], which must be realized by optimizing two competing tendencies, (i) the uniform $B = 0$ Meissner state of the superconductivity, and (ii) the uniform finite magnetization M with $B \neq 0$ of the ferromagnetism.

To consider such competition, as the first step, we adopt the spatially averaged treatment with the Pesch approximation [7], and minimize the averaged effective free-energy functional. The couplings between ferromagnetism and the superconductivity arise in (i) the gauge-invariant gradient term, (ii) the spin-dependent density of states (DOS), and (iii) the Zeeman term (negligible in the present situation). Since no double transitions have been observed, it is concluded that the splitting of DOS due to M is small enough based on the results of the residual specific-heat coefficient, γ. A possible transition between type-II and type-I superconductivity near the quantum critical point will also be discussed.

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