Antivortices in the mixed paramagnetic-orbital pair breaking regime

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Abstract

We consider a thin superconducing layer with a magnetic field direction slightly tilted from the plane-parallel orientation. In such a situation, which generalizes the FFLO state, both paramagnetic and orbital pair-breaking effects must be taken into account. We minimize the quasiclassical free energy to obtain the stable order parameter stucture near the upper critical field, extending previous work [U.Klein et al., J. Low Temp. Phys. 118 (2000) 91] with regard to magnetic field contributions. We find two-dimensional periodic states, characterized by Landau quantum numbers $n > 1$ showing antivortices, e.g. a unit-cell with three order parameter zeros (two vortices and an antivortex) carrying totally a single flux quantum. The underlying physical mechanism is different from a recent prediction of antivortices in mesoscopic samples of triangular shape [L. F. Chibotaru et al., Phys. Rev. Lett. 86 (2001) 1323].

Key words: Antivortices; FFLO state; orbital pair breaking; paramagnetic pair breaking

A superconducting antivortex changes its phase by -2π when encircling the centre and carries a corresponding flux quantum of negative sign. Such entities are sometimes introduced as purely mathematical constructs (called mirror vortices), in order to fulfill the Ginzburg-Landau(GL) boundary conditions at surfaces of superconductors [1]. They play also a role above the Kosterlitz-Thouless transition in thin superconducting films. However, individual antivortices have apparently not yet been identified experimentally.

Recently, a two-dimensional periodic state with a unit cell carrying a single flux quantum, two ordinary vortices, and a single antivortex has been predicted [2,3]. This state was found by minimizing the free energy for a thin-film configuration where both paramagnetic and orbital pair-breaking takes effect. Very recently, nucleation of antivortices in a mesoscopic superconducting triangle has been predicted [4]. Good agreement of the theoretical phase boundary with experimental data has been found [4]. The physical origin of the antivortices is quite different in these two cases. In the first case, we have a bulk phenomenon related to competing pair breaking effects; in the second case one has a combination of size effects and symmetry requirements. Formally, antivortices appear in both cases as a consequence of a mismatch between the number of zeros of the relevant set of basis functions and the required number of flux quanta per unit cell.

In this note we report on a study of antivortices in the mixed paramagnetic-orbital pair-breaking regime for superconductors of *finite* GL-parameter κ. Thereby, previous work [2,3] for London limit superconductors is extended to include magnetic field contributions.

We consider a quasi-two-dimensional superconductor in an external magnetic field whose direction φ can be varied (φ is the angle between the field and the conducting x,y-plane) [5]. We study a clean superconductor with a cylindrical Fermi surface of axial symmetry. This model describes conventional layered superconductors with (nearly) perfect 2D-behavior, i.e. extreme anisotropy and nearly perfect decoupling of the conducting layers.

The complete phase boundary H_{c2} between normal-conducting and superconducting state has been cal-

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culated by Shimahara and Rainer [6]. It has a cusp-like shape [1,4] with different pieces of the H_{c2} curve belonging to different values of the Landau quantum number n ($n = 0, 1, \ldots$). For large φ one finds $n = 0$, dominating orbital pair breaking and the usual vortex state. With decreasing φ states with higher n appear close to the plane-parallel orientation. For $\varphi \to 0$ one finds $n \to \infty$, only paramagnetic pair breaking remains, and the stable state [6] is the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state [7–13].

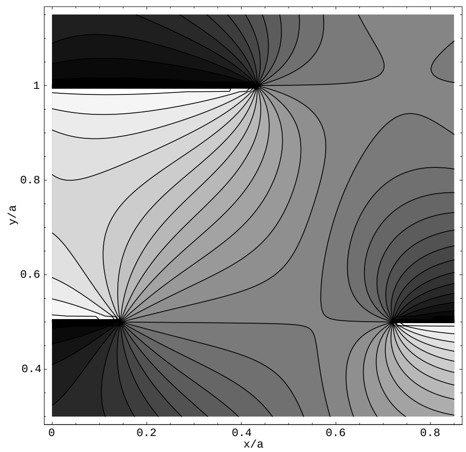

Fig. 1. Contour plot of phase of order parameter in triangular unit cell for $n = 2$ showing three order parameter zeros and associated branch cuts.

The structure of the superconducting states below H_{c2} has been calculated in Ref. [2] for a high-κ material. The quasi-periodic order parameter for a 2D-lattice with an angle α between the two basis vectors of length a and b may be constructed by standard methods:

$$\psi_n(x,y) = AC_n \sum_{m=-\infty}^{m=+\infty} \exp\left(-2\pi\imath\frac{b}{a}\cos\alpha\frac{m(m+1)}{2}\right) \times \cdot \exp\left(\frac{\imath}{\hbar}k_m x\right) h_n\left(y - mb\sin\alpha\right). \quad (1)$$

Here, $k_m = (2\pi\hbar/a)m$ and the function h_n is proportional to a Hermite polynomial of order n (see Ref. [2] for further details). To find the stable lattice structure (the parameters a, b, α) for given n, T, the quasiclassical free energy including nonlinear terms has to be minimized. For $n \geq 2$ several stable states showing antivortices have been found. The $n = 2$ state (see Fig. 3 of Ref. [2]) appearing at the largest φ, is the one most easily accessible experimentally.

This treatment has been generalized with regard to effects of finite κ [14]). Taking magnetic field contributions into account allows one to recover (from the $n = 0$ state) Abrikosovs solution in the GL-limit and to identify the transition between type II and type I behavior. An essential result with regard to antivortex states is the fact that the $n = 2$ structure, found in Ref. [2] remains stable (in contrast to most other states) for a very wide range of κ-values (calculations have been performed for $0.1 \leq \kappa \leq 100$ at two T). The equilibrium structure is the same as in [2]. To show the presence of antivortices more explicitely, the *phase* of the order parameter is plotted in Fig. 1 (its absolute value is shown in Fig.3 of [2]). There are three zeros of the order parameter per unit cell, each one being the starting point of an associated branch cut. When traversing a branch cut from the black side to the white side, the phase increases by 2π. Encircling the vortex centers in anticlockwise direction, one sees that the upper vortex is an antivortex (phase change by -2π) while the two lower vortices are of the ordinary ($+2\pi$) type. The unit cell as a whole carries a single flux quantum, corresponding to a total phase change of $+2\pi$.

Summarizing, we considered a 2D superconducting film in a tilted magnetic field where both orbital and paramagnetic pair-breaking takes effect. Using a material with a circular Fermi surface and an arbitrary GL parameter κ, a quasiperiodic superconducting state ($n = 2$) with a vortex-antivortex pair and an ordinary vortex per unit cell should appear for applied field nearly parallel (within an angle of the order of 1 degree) to the conducting plane.

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