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Vortex charge in a system with tightly bound electron pairs

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Abstract

We investigate the superconducting vortex within a boson–fermion model, that describes a system of itinerant electrons and mobile electron pairs (bosons). In particular, we investigate profiles of the order parameters in the fermionic and bosonic subsystems as well as the effective vortex charge. We demonstrate that the vortex charge is determined predominantly by concentration of the tightly bound electron pairs and is much larger than in purely fermionic systems. This result remains in agreement with the recent measurements, which show that in high-T_c superconductors the vortex charge is much larger than predicted by the BCS theory.

Keywords: Superconductivity; Boson–fermion model; Mixed state

Many unusual properties of high-T_c superconductors (HTSC), have successfully been described within the boson–fermion model (BFM) that involves tightly bound electron pairs (bosons) and itinerant electrons [1]. In particular, the BFM correctly describes opening of the pseudogap and its evolution into the superconducting gap [2], a non-BCS ratio $\Delta/k_B T_c$ [1] and the unusual temperature dependence of the upper critical field [3]. Another interesting feature of HTSC concerns the vortex charge. It has recently been observed that the sign of the vortex charge may reverse with doping [4], whereas its magnitude is much larger than predicted by the BCS theory. The effective vortex charge has been analyzed within the BFM in a highly simplified case of localized bosons [5], i.e., when bosons are not affected by the magnetic field.

Here, we investigate properties of the superconducting vortex in a two-dimensional system, that consists of both itinerant electrons and itinerant bosons:

$$\mathcal{H}^{\mathrm{BF}} = \sum_{\langle ij\rangle\sigma}(t_{ij}(\mathbf{A}) - \delta_{ij}\mu)c^{\dagger}_{i\sigma}c_{j\sigma} + \sum_{\langle ij\rangle}(\omega_{ij}(\mathbf{A}) + \delta_{ij}E_{\mathrm{B}})b^{\dagger}_{i}b_{j} + V\sum_{i}(b^{\dagger}_{i}c_{i\downarrow}c_{i\uparrow} + \mathrm{h.c.}). \tag{1}$$

Bosons ($b_i^{(\dagger)}$) and electrons ($c_{i\sigma}^{(\dagger)}$) interact via the charge exchange interaction V. In Eq. (1) μ is the chemical potential and $E_B = \varepsilon_B - 2\mu$, where ε_B is the bosonic level. $t_{ij}(\mathbf{A})$ and $\omega_{ij}(\mathbf{A})$ are the nearest-neighbor hopping integrals for fermions and bosons, respectively. These quantities depend on the external magnetic field through the vector potential $\mathbf{A}$, as follows from the Peierls substitution. Since bosons are doubly charged with respect to fermions, the Peierls phase in $\omega_{ij}(\mathbf{A})$ is twice as large as in $t_{ij}(\mathbf{A})$.

In order to investigate the vortex structure, we apply the mean-field decoupling for the boson–fermion interaction: $Vb_i^{\dagger}c_{i\downarrow}c_{i\uparrow} \simeq V\alpha_i^* c_{i\downarrow}c_{i\uparrow} + b_i^{\dagger}\Delta_i$, where $\Delta_i = V\langle c_{i\downarrow}c_{i\uparrow}\rangle$ and $\alpha_i = \langle b_i\rangle$. Then, the effective Hamiltonian consists of separated fermionic and bosonic parts, $\mathcal{H}^{\mathrm{BF}} = \mathcal{H}^{\mathrm{F}} + \mathcal{H}^{\mathrm{B}}$. These two subsystems are coupled through the chemical potential and the order parameters Δ_i, α_i. The fermionic part of the Hamiltonian, $\mathcal{H}^{\mathrm{F}}$, can be diagonalized with the help of the Bogoliubov–de Gennes (BdG) transformation [6]. The bosonic part of the Hamiltonian, $\mathcal{H}^{\mathrm{B}}$, can be diagonalized in two subsequent steps. First, we introduce bosonic operators $\tilde{b}_i = b_i - \alpha_i$ in such a way that $\mathcal{H}^{\mathrm{B}}$, when expressed in terms of $\tilde{b}_i$, takes on the form of a Hamiltonian of non-interacting bosons. One can show, that

$$\mathcal{H}^{\mathrm{B}} = \sum_{\langle ij\rangle}(\omega_{ij}(\mathbf{A}) + \delta_{ij}E_{\mathrm{B}})(\tilde{b}^{\dagger}_{i}\tilde{b}_{j} + \alpha^{*}_{i}\alpha_{j}) \tag{2}$$

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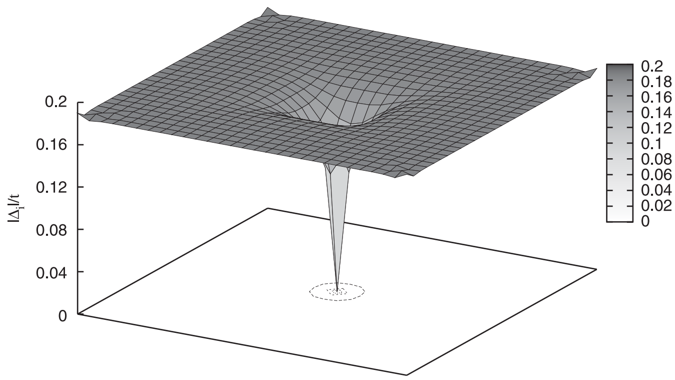

Fig. 1. Δ_i in the vicinity of the vortex core. We have found that in the vicinity of the vortex core $\alpha_i \simeq 1.9\Delta_i/t$.

provided α_i fulfill the set of linear equations: $\Delta_i = E_B\alpha_i + \sum_j \omega_{ij}(\mathbf{A})\alpha_j$. Then, we make use of a unitary transformation and introduce $B^\dagger_{m\sigma} = \sum_i \tilde{b}^\dagger_{i\sigma} U_{im}$, where the unitary matrix U_{im} consist of eigenvectors of the hermitian matrix $\omega_{ij}(\mathbf{A})$. $\mathscr{H}^B$, when expressed in term of B-operators, represents a diagonal one-particle Hamiltonian.

Since the fermionic and bosonic subsystems are coupled through the order parameters the Bogoliubov–de Gennes equations have to be solved self-consistently together with the above procedure, that leads to a diagonal form of $\mathscr{H}^B$. Below, we discuss the numerical results obtained for 35×35 lattice and for $\varepsilon_B = 0.5, V = 1.0t, k_B T = 0.05t, \mu = -0.1t$. We have assumed that the bosonic bandwidth is $\frac{1}{20}$ of the fermionic one. The qualitative results do not depend on the specific choice of the model parameters provided the width of fermionic band is much larger than the bosonic one.

We have found that both the order parameters Δ_i and α_i vanish in the vortex center and have the same phase. Although the present approach significantly differs from the BdG equations derived for a purely fermionic system [6], both the order parameters can be well fitted by the commonly used formula for the vortex profile: $|\Delta_i| = |\Delta_0| \tanh r/\xi$ and $|\alpha_i| = |\alpha_0| \tanh r/\xi$, where r is the distance from the vortex center and ξ characterizes the size of the vortex core. We have found that an approximate linear relation $\alpha_i \simeq a\Delta_i$ holds, however the value of the coefficient a depends on the model parameters. Therefore, in Fig. 1 we show the spatial dependence of Δ_i only.

The most important results concerning the concentration of electrons, n_i^F, and the bound electron pairs, n_i^B, are shown in Fig. 2. The concentration of fermions in the vortex core is almost the same as their concentration away from the vortex. This result originates from the fact that the superconducting gap is much smaller than the bandwidth and, therefore, vanishing of this gap in the vortex core is responsible only for a small change of the Fermi

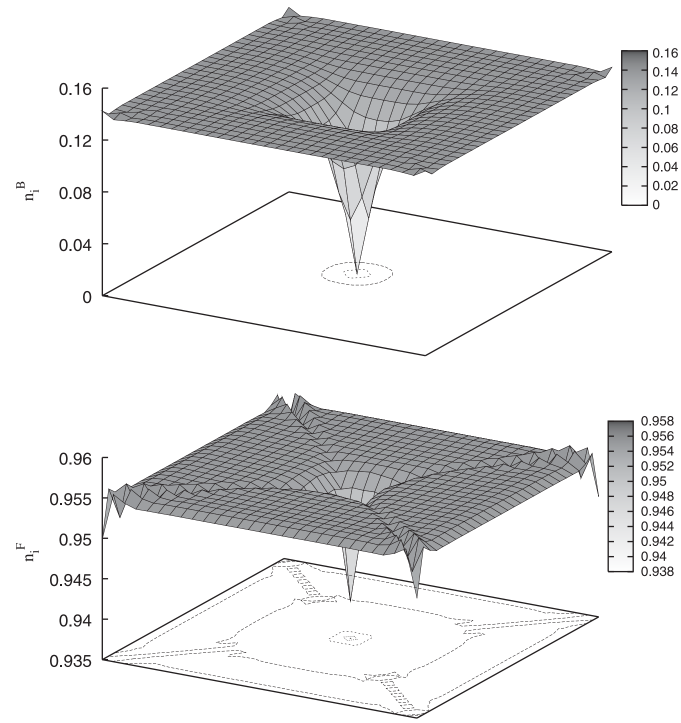

Fig. 2. Concentration of the tightly bound electron pairs (upper panel) and itinerant electrons (lower panel) in the vicinity of the vortex core.

energy. However, in the case of bosons, the inhomogeneity of their concentration is significant, as can be inferred from Fig. 2. In order, to estimate the fermionic and bosonic contributions to the vortex charge, we have calculated the following quantities: $Q^B = 2\sum_i n^B_\infty - n^B_i$ and $Q^F = \sum_i n^F_\infty - n^F_i$, where n^B_∞ and n^F_∞ denote the concentration of bosons and fermions away from the vortex core. The factor 2 in the bosonic contribution originates from the fact, that bosons are doubly charged with respect to fermions. We have found that $Q^B \simeq 6$ and $Q^F \simeq 0.15$, what clearly demonstrates that the inhomogeneous concentration of bosons gives the dominating contribution do the effective vortex charge. To summarize, we have shown that the BFM may explain the large values of vortex charge observed in HTSC.

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