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UNCONVENTIONAL SUPERCONDUCTIVITY IN STRONG MAGNETIC FIELD

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The Landau quantization effects are considered in low carrier concentration unconventional spin triplet p-wave superconductors in a high magnetic field region. The field dependence of the superconducting order parameter and the vortex lattice states for intra Landau level pairing are analyzed. The gap functions are calculated within mean field approximation.

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1. Introduction

The Landau quantization of charge carriers introduced into the BCS-type theory leads to quite new behaviour of the conventional type-II superconductors in a high magnetic field limit region [1–5]. In this paper we analyze the Landau quantization effects in superconductors with one of the simplest unconventional pairing neglecting both the Zeeman splitting and the spin–orbit interaction. On the basis of the Green function method we discuss an influence of Landau quantization of the p-wave type pairing on the gap function and spatial dependence of the superconducting order parameter as well.

When cut-off energy of the attractive couplings is lower than the cyclotron frequency then the pairing occurs only within the last occupied single n-th Landau level.

Thus the pairing Hamiltonian in a plane perpendicular to the quantizing field B has the form

$$H = \sum_{\boldsymbol{k},\sigma,n} (\varepsilon_n - \mu) c^{\dagger}_{\boldsymbol{k},\sigma} c_{\boldsymbol{k},\sigma} - \frac{1}{2} \sum_{\boldsymbol{k},\boldsymbol{k}',\sigma,\sigma'} V_{\boldsymbol{k}\boldsymbol{k}'} c^{\dagger}_{\boldsymbol{k},\sigma} c^{\dagger}_{-\boldsymbol{k}',\sigma'} c_{-\boldsymbol{k}',\sigma'} c_{\boldsymbol{k},\sigma}, \tag{1}$$

where ε_n is the energy of the n-th Landau level and μ stands for the Fermi level. The local, p-symmetry and spin independent interaction term $V_{\boldsymbol{k}\boldsymbol{k}'}$, which at zero magnetic field is proportional to the scalar product $\boldsymbol{k} \cdot \boldsymbol{k}'$, can be decomposed into the following sum of $n+1$ products whose form is analogous to that in [5]:

$$V_{\boldsymbol{k}\boldsymbol{k}'} = \sum_{j=0}^{n} A_{nj} \sum_{p=0,1} \chi^{p*}_{2j+1}(\boldsymbol{k}) \chi^{p}_{2j+1}(\boldsymbol{k}'), \tag{2}$$

where

$$\chi_j^p(\boldsymbol{k}) = \sqrt{l} \sum_{\nu=-\infty}^{+\infty} \mathrm{e}^{-\mathrm{i}k_x(2\nu+p)d} \phi_j^{\mathrm{osc}} \left\{ \frac{l^2}{\sqrt{2}} \left[2k_y + (2\nu+p)\frac{\pi}{d} \right] \right\}. \tag{3}$$

l is the magnetic length unit, $-q_{x,y} < k_{x,y} \leq q_{x,y}$, $q_{x,y} = \pi/d$, and $d = l\sqrt{\pi}$ is the magnetic lattice constant. Here $\phi_j^{\mathrm{osc}}(x)$ is the j-th Landau level function. The second quantization operator $c_{\boldsymbol{k},\sigma}$ annihilates the electron in the spin state $\sigma = \uparrow, \downarrow$ and the orbital one chosen as an appropriate superposition of the j-th Landau level functions which incorporates the symmetry of the Abelian magnetic translation group [3, 4]. These functions are shifted along the x axis and multiplied by the plane wave in the y direction.

Actually, in the mean field approximation, the triplet pairing gap functions depend on $n+1$ amplitudes Δ_j^p:

$$\Delta_{\boldsymbol{k}}^{\sigma\sigma'} = -\sum_{j=0}^{n} \sum_{p=0,1} A_{nj} (\Delta_j^p)^{\sigma\sigma'} \chi_{2j+1}^{p*}(\boldsymbol{k}), \tag{4}$$

where Δ_j^p are solutions of the following set of self-consistent equations:

$$(\Delta_j^p)^{\sigma\sigma'} = \sum_{j'=0}^{n} \sum_{p'=0,1} K_j^{pp'} (\Delta_{j'}^{p'})^{\sigma\sigma'}. \tag{5}$$

The kernels and the quasiparticle energy are given by

$$K_{jj'}^{pp'} = A_{nj} \sum_{\boldsymbol{k}} \chi_{2j+1}^{p}(\boldsymbol{k}) \chi_{2j'+1}^{p'}(\boldsymbol{k}) \frac{1 - 2f(E_{\boldsymbol{k}})}{2E_{\boldsymbol{k}}}, \tag{6}$$

$$E_{\boldsymbol{k}} = \sqrt{(\varepsilon_n - \mu)^2 + \Delta_{\boldsymbol{k}}^2}, \tag{7}$$

respectively. Here $f(E)$ denotes the Fermi distribution function and $\Delta_{\boldsymbol{k}}^2 = |\Delta^{\uparrow\uparrow}|^2 + |\Delta^{\uparrow\downarrow}|^2$. For p-wave superconductors in a strong magnetic field we can define the superconducting order parameter in a way similar to that given in [6] (for details see [5])

$$\Delta^{\sigma\sigma'}(\boldsymbol{r}) = -\frac{V}{k_{\mathrm{F}}} \langle \psi_\sigma(\boldsymbol{r}) (\Pi_x - \mathrm{i}\Pi_y) \psi_{\sigma'}(\boldsymbol{r}) \rangle, \tag{8}$$

where $\psi_\sigma(\boldsymbol{r})$ is the appropriate field operator, $\Pi_j = \frac{\partial}{\partial x_j} - \mathrm{i}\frac{e}{\hbar}A_j$ is the j-th component of the momentum operator, $\boldsymbol{A}$ is the vector potential; $x_j = x$ or y, and k_{F} stands for the Fermi wave vector. V describes strength of local pairing interaction. The gap function is gapless at the set of points $\boldsymbol{Q}_i$ in the magnetic Brillouin zone which are in direct correspondence with positions of the vortices in real space $|\boldsymbol{r}_i| = |\boldsymbol{Q}_i| l^2$. Configuration of the nodes in the gap function and corresponding vortices reflect the centre of mass motion of Cooper pairs in quantizing magnetic field.

2. Results and conclusions

Finally, we can say that the Landau quantization of the charge carriers introduced into the BCS-type theory leads to quite new behaviour of the type II p-wave superconductors in a strong magnetic field. In particular, in p-wave superconductors with local isotropic attractive interactions between electrons within the n-th Landau level there exist $n+1$ different channels of pairing.

Such multichannel character of the gap function for p-wave superconductors was first recognized in Ref. [5]. The all possible gap amplitudes Δ_j, for a given Landau level n, vanish at the same temperature T_C. Thus, all the channels for triplet superconductors are equivalent with respect to Cooper pairing.

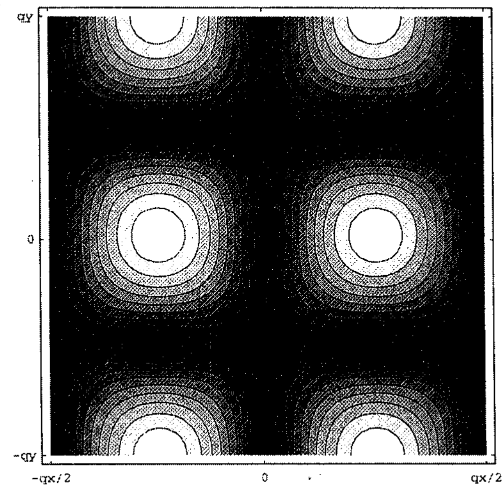

Fig. 1. Gap function $|\Delta_{\boldsymbol{k}}|$ of the square-vortex lattice for the p-wave intra $n=1$ level pairing superconductor.

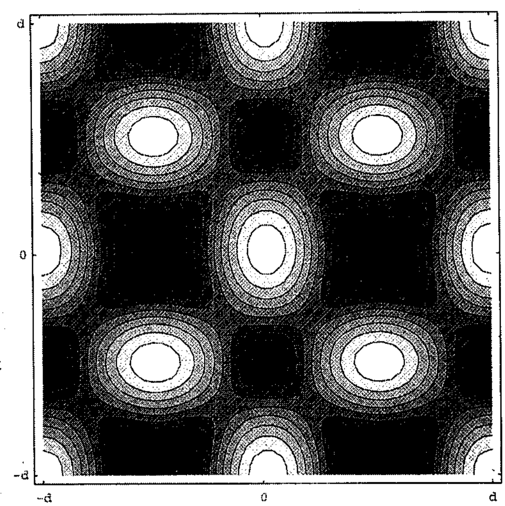

Fig. 2. Contour plot of the absolute value of the order parameter $|\Delta^{\sigma\sigma'}(\boldsymbol{r})|$ in real space for the p-wave pairing within $n=1$ Landau level.

The magnetic field dependence of the transition temperature $T_c(B)$ displays characteristic magneto-quantum oscillations reflecting the Landau level structure [5].

In Figs. 1 and 2 there are displayed contour plots of the gap function $\Delta_{\boldsymbol{k}}$ and the order parameter $\Delta^{\sigma\sigma'}(r)$ for p-wave pairing within the single $n = 1$ Landau level.

The spatial variation of the order parameter evidently depends on the order n of the Landau state involved in the pairing process. The complexity of the obtained vortex structures increases with n. In our analysis the spatial variation of superconducting order parameter preserve only one positive flux quantum per unit magnetic cell.

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