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Study of a high-temperature superconductor under pressure

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Abstract

We consider a Ginzburg–Landau modified model for a high-temperature superconductor under pressure. We have theoretically studied the relation between the outer pressure and the temperature of the high-temperature superconductor. In a special case this relation is determined by a first-order partial differential equation. We find that the critical temperature decreases quasi-linearly with increasing pressure. In another special case, we obtain that the critical temperature increases quasi-linearly with increasing pressure.

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1. Introduction

In the last few years, there is a noticeable increase of the study of superconductivity in many elements under pressure. Recently pressure-induced superconductivity has been found in UGe_2. This finding is quite interesting, since the superconductivity appears in the pressure range from 1.0 to 1.6 GPa where UGe_2 is still in the ferromagnetic state. This is the first discovery that the same 5f electrons are involved with both orderings [1,2].

The discovery of unconventional superconductivity has caused an explosive growth of activities in various fields of condensed-matter research, not only studies of the basic mechanisms leading to this phenomenon, but also a widespread search for new technological applications. Different behaviors have been observed in heavy-fermion materials [3,4–15], in organic conductors [16,17], copper oxides etc. [18–20]. These findings suggest that the mechanism forming Cooper pairs can be magnetic in origin. Namely, on the verge of magnetic order,

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the magnetically soft electron liquid can mediate spin-dependent attractive interactions between the charge carriers [14]. However, the nature of superconductivity and magnetism is still unclear when the superconductivity appears very close to the antiferromagnetism (AFM). The mechanism of the superconductivity and the symmetry of the order parameters are the main puzzles of on-going research.

Here, we consider a Ginzburg–Landau (TDGL) modified model to study the properties of a high-temperature superconductor under pressure.

2. The model

Before discussing vortex motion, we consider the modified TDGL and theoretically study some properties of a high-temperature superconductor as a function of pressure. The pressure will apply work to the high-temperature superconductor. Simultaneously, the internal energy of the high-temperature superconductor is increased. The modified Ginzburg–Landau free energy of a superconductor is [21–24]

$$F = \int \mathrm{d}V \left\{ \bar{a}|\Psi(\mathbf{r})|^2 + \bar{\mu}|\Psi(\mathbf{r})|^2 + \frac{1}{2} b|\Psi(\mathbf{r})|^4 + \frac{\hbar^2}{2m}\left|\left(-\mathrm{i}\nabla - \frac{2e}{c}\mathbf{A}\right)\Psi(\mathbf{r})\right|^2 + \frac{\mathbf{H}^2}{8\pi}\right\}. \quad (1)$$

Our equation of vortex motion for the superconductive order parameter $\Psi(\mathbf{r}, t)$ is [21,23,24]

$$\left[\partial_t + \frac{\mathrm{i}\Omega}{\hbar}\right]\Psi = -\Gamma\frac{\delta F}{\delta\Psi^*}, \quad (1')$$

where $\bar{a} = a_0((T/T_C) - 1)$, $\bar{\mu} = \mu_0(p_0 - p)$, T denotes the temperature, μ_0 and a_0 are constants, p_0 is the initial pressure, p is the pressure acting on the high-temperature superconductor; b is the usual Landau parameter; $e = 1.6 \times 10^{-19}$ coulomb; Ω is the total chemical potential of the high-temperature superconductor, m is the effective mass of a moving quasi-particle; V is the total volume of the high-temperature superconductor; $\mathbf{A}$ is the outer vector potential, $\mathbf{H}$ is the outer magnetic field; $\mathbf{B} = \langle\mathbf{h}\rangle$ is the induction field, $\mathbf{h} = \nabla \times \mathbf{A}$ is the microscopic magnetic field, and Ψ is the order parameter. We neglect the anisotropy in the high-temperature superconductor [18–20]. The order parameter is usually expressed as $\Psi = f\exp[\mathrm{i}\delta(r,t)]$, $\int \Psi^*\Psi\,\mathrm{d}V = V$. Here f is an amplitude. Note that a moving vortex does not possess cylindrical symmetry, so the phase variable δ is equal to the angular variable only near the center of the vortex [21,22,25]. We also require an equation of motion for the vector potential. Ampère's law $\nabla \times \nabla \times \mathbf{A} = 4\pi(\mathbf{J_n} + \mathbf{J_s})$ is to be obeyed by the vector potential, so that $\nabla \cdot (\mathbf{J_n} + \mathbf{J_s}) = 0$. Consequently, the magnetic field has the vortex structure. We have

$$-\frac{\hbar^2}{2m}\left(\frac{\partial}{\partial\mathbf{r}} - \frac{2\mathrm{i}e}{c}\mathbf{A}\right)^2 = -\frac{\hbar^2}{2m}\nabla^2 + \frac{2\mathrm{i}e\hbar}{mc}\mathbf{A}\cdot\nabla + \frac{(2e)^2}{2mc^2}\mathbf{A}^2.$$

We consider $a = \bar{a} + \bar{\mu}$ to depend on temperature and pressure. From Eq. (1), we have

$$\frac{\delta F}{\delta\Psi^*} = \int \mathrm{d}V\left\{a\Psi + b|\Psi|^2\Psi - \frac{\hbar^2}{2m}\left(\frac{\partial}{\partial\mathbf{r}} - \frac{2\mathrm{i}e}{c}\mathbf{A}\right)^2\Psi\right\}. \quad (2)$$

Here, a proper choice of f will allow all of the above equations to be solved exactly [24,26–28]. This is the method originally developed by Schmid who assumed an approximate order-parameter profile of the form [24,26] $f(r) = Kar/[r^2 + \xi_v^2]^{1/2}$, where K is a constant, ξ_v is a healing length of the order parameter and numerically close to 1 [23].

3. Characterization of thermodynamics

We know the main quantities of thermodynamics from the general principle of thermodynamics and statistics. For example, free energy $F = U - TS$, inner energy $U = F - T(\partial F/\partial T)$, $\mathrm{d}F = -S\,\mathrm{d}T - p\,\mathrm{d}V$, expansion coefficient $\alpha = (1/V)(\partial V/\partial T)_p$, pressure coefficient $\beta = (1/p)(\partial p/\partial T)_V$, compressibility coefficient $\kappa = -(1/V)(\partial V/\partial p)_T$, heat capacity $C_V = (\partial U/\partial T)_V = T(\partial S/\partial T)_V$, $C_p = (\mathrm{d}Q/\mathrm{d}T)_p = T(\partial S/\partial T)_p$, and