INFLUENCE OF FLUCTUATIONS ON THE LONDON PENETRATION DEPTH

A. Buzdin and B. Vuyichit'*

* Physics Department, Moscow State University, 117234 Moscow, USSR;
also: University of Titograd, Faculty of Science, P.O.Box 211, 81000 Titograd, Yugoslavia

The fluctuation contribution to London penetration depth λ is calculated in the Gaussian approximation. It occurs to be directly related with the fluctuation correction to specific heat and then may be observable in single crystal of high-T_c superconductors.

Due to small coherence lengths the fluctuation effects in high-T_c superconductors are much more pronounced than in the usual superconductors. It is revealed by conductivity [1] and, especially, by specific heat [2] measurements. To our knowledge it is the first experimental observation of fluctuation contribution to specific heat in bulk superconductors. Also, fluctuations must affect the London penetration depth λ and lead to the deviation from the simple linear temperature dependence of $\lambda^{-2}(T)$ near T_c. It is important to note that in this case the fluctuation contribution to $\lambda^{-2}(T)$ is not restricted to fluctuations of square of the modulus of superconducting order parameter $|\psi|^2$.

The general expression for free energy which includes fluctuations is

$$F = T \ln \int \exp\left(- H_{eff}(\psi)/T \right) D\psi, \tag{1}$$

where the effective Hamiltonian H_{eff} coincides (except unimportant renormalization of critical temperature) with Ginzburg - Landau functional (see e.g. [3])

$$H_{eff}(\psi) = \int \left\{ a\, |\psi|^2 + \frac{b}{2}\, |\psi|^4 + \sum_i \frac{1}{4m_i} \left| (\nabla_i - \frac{2ie}{c} A_i)\, \psi \right|^2 \right\} d^3\vec{r}. \tag{2}$$

For $H_{eff}(\psi)$ we use the anisotropic mass approximation with: $m_z \gg m_x, m_y$,

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corresponding to the case of layered superconductors near T_c.

To calculate the functional integral (1) in the Gaussian approximation we put order parameter in the form $\psi = \psi_0 + \psi_1$, where $\psi_0^2 = |a|/b$ is the equilibrium value of the order parameter at $T < T_c$, and ψ_1 is due to fluctuations ($\psi_1 \ll \psi_0$). Then

$$\delta H_{eff}(\psi_1) = \int \left\{ \frac{1}{2} |a| \left[2|\psi_1|^2 + \psi_1^2 + \overset{*}{\psi}{}_1^2 \right] + \sum_i \frac{1}{4m_i} |(\nabla_i - \frac{2ie}{c} A_i)\psi_1|^2 \right\} d^3\vec{r}, \tag{3}$$

and the fluctuation contribution to the free-energy is

$$F_{fl} = - T \ln \int \exp\left(- \frac{\delta H_{eff}(\psi_1, \vec{A})}{T} \right) D\psi_1 . \tag{4}$$

The additional current due to fluctuations is

$$\vec{J}_{fl} = - \frac{\delta F_{fl}}{\delta \vec{A}} . \tag{5}$$

In type-II superconductors with $\varkappa \gg 1$, in the calculation of F_{fl} and $\vec{J}_{fl}$ we may consider vector-potential $\vec{A}$ as a constant. Indeed, the characteristic length scale for $\vec{A}(\vec{r})$ change is of the order of $\lambda(T)$, whereas the characteristic length scale for $\psi(r)$ fluctuation is $\xi(T)$, and $\xi(T) \ll \lambda(T)$.

Performing functional integration in (4) we have

$$F_{fl} = - \frac{T}{2} \sum_{\vec{k}} \ln \left\{ \frac{\pi^2 T^2}{\left[\sum_i \frac{1}{4m_i}(k_i - \frac{2e}{c} A_i)^2 + |a| \right]\left[\sum_i \frac{1}{4m_i}(k_i + \frac{2e}{c} A_i)^2 + |a| \right] - a^2} \right\}. \tag{6}$$

After some calculations we obtain a simple expression for the London penetration depth $\lambda_i^{-2} = 4\pi j_i/cA_i$ which take into account Gaussian fluctuations, namely

$$\lambda_i^{-2} = \lambda_{0,i}^{-2} \left(1 - \frac{1}{3} \sqrt{\frac{Gi}{t}} \right), \tag{7}$$

where $\lambda_{0,i}^{-2} = (8\pi e^2/m_i c^2)|\psi|/b$, $t = (T_c - T)/T_c$, and $Gi = 2T_c m_1 m_2 m_3 b^2/(\pi^2 \alpha)$ is so called Ginzburg number [3].

Note that although the London penetration depth is anisotropic, the relative contribution of fluctuations is isotropic. As follows from expression (7), the temperature dependence of $\lambda^{-2}(T)$ will have additional $\sim t^{1/2}$ term beside in addition to the usual linear form ($\sim t$).

The expression for specific heat including Gaussian fluctuations at $T <$ $< T_c$ is (see e.g.[4])

$$C(T) = \Delta C_0 \left(1 + \sqrt{\frac{Gi}{t}}\right), \tag{8}$$

$\Delta C_0 = \alpha^2 / T_c b$ - specific heat jump in mean field approximation. Comparing expression (7) and (8), we can see that the relative contribution of fluctuation effects to λ^{-2} is one third, as compared with that in the specific heat.

We may estimate from the experimental data [2] the fluctuation region in $YBa_2Cu_3O_{7-\delta}$ as 3-4 K (i.e., Gi is of the order of some percent). In this region we expect that the fluctuation contribution (7) to λ^{-2} may be observed. The precise measurements of $\lambda^{-2}(T)$ and $C(T)$ dependences near T_c in single crystals of high-T_c superconductors could reveal direct relation (see (7), (8)) between fluctuation contribution, to the London penetration depth and the specific heat.

In the case of Josephson coupling of the layers the anisotropic Ginzburg - Landau functional (2) is applicable only in the immediate vicinity of the critical temperature T_c. At lower temperatures two-dimensional fluctuation regime is realized with different temperature dependence of fluctuation contribution to λ^{-2}.

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