# Model of self-induced fluctuation superconductivity

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A model of a first-order superconducting phase transition (of the gas–liquid type) in systems with mobile defects is analyzed. The transition temperature depends on the concentration of these defects.

We would like to propose a new model for which superconductivity arises as a result of a first-order phase transition, for superconductors with a structure which changes easily. We have in mind substances which contain mobile structural defects (vacancies, impurities, etc.) which can form inhomogeneous spatial distributions through diffusion. The model does not depend on the superconducting condensation mechanism. In terms of the underlying concepts, the model is similar to the fluctuon model.[1] The model is based on a dependence of the local superconducting transition temperature $T_c(\mathbf{r})$ on the local defect concentration $\eta(\mathbf{r})$. In the simplest case, this would be a linear dependence

$$T_c = \bar{T}_c + \Gamma\delta\eta, \quad \Gamma = \text{const} \tag{1}$$

Here $\delta\eta = \eta - \bar{\eta}$ is the deviation of the defect concentration from its mean value $\bar{\eta}$, and $\bar{T}_c = T_c(\bar{\eta})$. For definiteness, we assume that the constant $\Gamma$ is positive, an we express the concentration in dimensionless units, $0 < \eta < 1$. By virtue of dependence (1), a local fluctuation of the concentration $\eta$ leads to an increase in $T_c$. At temperatures $T < T_c$, this effect lowers the free energy by virtue of a superconducting condensation of electrons:

$$\delta F_1 = -V\frac{\alpha^2}{2b}(T_c - T)^2, \qquad T < T_c, \tag{2}$$

where $\alpha$ and $b$ are the parameters of the Ginzburg–Landau functional, and $V$ is the volume of the fluctuation region. An important point here is that the fluctuation $\delta\eta$ may form, and the energy may decrease as in (2), as a result of the motion of mobile defects.

On the other hand, the onset of a fluctuation increases the free energy by an amount $\delta F_2 = -T\delta S$, where $\delta S$ is the change in entropy. For simplicity we restrict the analysis to small fluctuations ($\delta\eta \ll \bar{\eta}$), in which case we can write

$$\delta F_2 = \frac{1}{2}T\frac{V}{v_0}(\delta\eta)^2\left(\frac{1}{\bar{\eta}} + \frac{1}{1-\bar{\eta}}\right), \tag{3}$$

where $v_0$ is the volume of a unit cell.

The benefit in free energy due to the superconducting condensation, $\delta F_1$, is greater than the penalty $\delta F_2$ if the temperature satisfies

  

$$T < T^* = \alpha^2 \Gamma^2 v_0 \bar{\eta}(1-\bar{\eta})/b, \tag{4}$$

and if the fluctuation $\delta\eta$ exceeds the value

$$\delta\eta^* = \frac{\delta\eta_c}{1-(T/T^*)^{1/2}}, \quad \delta\eta_c = \frac{T-\overline{T}_c}{\Gamma}, \tag{5}$$

where $\delta\eta_c$ is the concentration corresponding to the superconducting transition at the given temperature (Fig. 1). If conditions (4) and (5) do hold, superconductivity will occur in the fluctuation region at $T > \overline{T}_c$.

Self-induced spatial fluctuations in the distribution of mobile defects can thus lead to a local increase in the superconducting transition temperature. If this effect does occur, the sample will spontaneously break up into a two-phase system, formed by superconducting ($S$) and normal ($N$) regions. The transition to a superconducting state is a first-order phase transition in this case. If the superconducting regions furthermore form a connected system, there will be a macroscopic superconductivity in the sample.

It can be seen from Fig. 1 that the energy benefit improves with increasing value of the concentration $\eta$ in the superconducting region. Actually, however, this concentration is limited by the mutual repulsion of defects at $\delta\eta_{\max} \approx 1$ (Fig. 1). The characteristic concentration $\delta\eta^*$ in (5) must therefore satisfy the condition $\delta\eta^* < 1$. The minimum size $R$ of the fluctuation region (the size of the critical nucleation region) is found from the condition $R > \xi$, where $\xi$ is a temperature-dependent coherence length.

Quadratic approximation (3) leads to an overestimate of the entropic component of the free energy. For fluctuations which are not too small, $|\delta n| \approx \bar{\eta}$, the function $\delta F_2(\eta)$ approaches a linear law, and the conditions for the appearance of $S$ regions become easier to satisfy. An analysis of the case of arbitrary fluctuations $\delta\eta$ is more involved, and we will not go into it here.

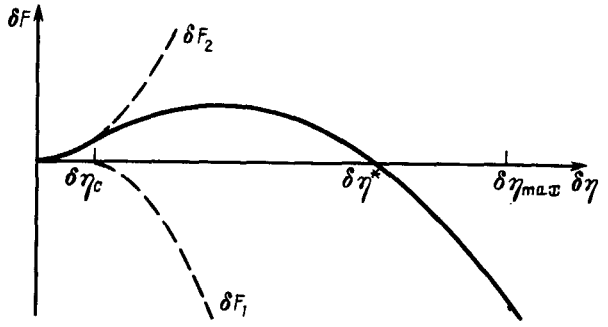


FIG. 1. The free energy $\delta F = \delta F_1 + \delta F_2$ versus the dimensionless defect concentration. The dashed lines show the entropic and superconducting components. The value $\delta\eta_{\max}$ is the corresponding maximum attainable defect concentration.

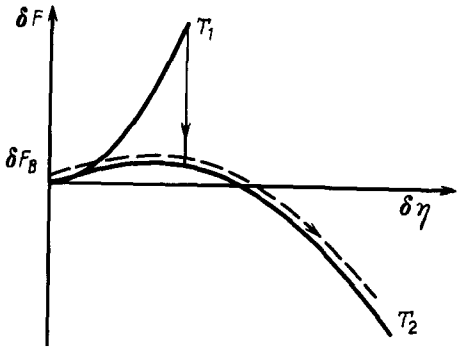


FIG. 2. Free energy versus the defect concentration at two temperatures, $T_1 > T^*$ and $T_2 < T^*$. Solid arrow—transition to the low-temperature $S$ phase as a result of rapid cooling; dashed arrow—transition associated with the formation of critical nucleation regions as the result of a diffusion of defects; $\delta F_B$—height of the thermodynamic barrier.

The rate at which the fluctuation $S$ regions form depends on two factors: the height of the thermodynamic barrier of the transition and the defect diffusion coefficient. Here we will point out two ways in which nucleation regions of the $S$ phase might form. The first involves a freezing of high-temperature thermodynamic fluctuations in the defect concentration during a rapid cooling (Fig. 2). The second involves the formation of critical $S$-phase nucleation regions at a low temperature ($T < T^*$) as a result of diffusion (the diffusion rate might be increased by irradiating the material). The force exerted on the defects by the superconducting condensate, which is proportional to the gradient of the square modulus of the order parameter, must be kept in mind.

A magnetic field can affect the growth of the $S$ phase nucleation regions, restricting their size to the magnetic length (in type-II superconductors). In addition, the imposition of a magnetic field after the formation of the $S$ phase will result in a displacement of defects from the cores of vortex filaments into the interior of the $S$ phase. Experimentally, features of this type in the kinetics of the growth and decay of the $S$ phase can lead to hysteresis effects, long-term relaxation processes, aging, and a nonreproducibility due to diffusion of defects. Since the diffusion of defects is usually a thermally activated process, this model would hardly apply to conventional "low-temperature" superconductors. It might, however, be pertinent to the high-temperature superconductors with $T_c \approx 100$ K and with comparatively low diffusion barriers which have recently been the subject of active research.[2] In such superconductors, the superconducting transition temperature is known to be a strong function of the oxygen content. There is evidence, moreover, for the existence of normal excitations in these materials at low temperatures[3,4] ($T \ll T_c$). There is also evidence for the existence of superconducting correlations at[5,6] $T > T_c$. Finally, a correlated arrangement of oxygen vacancies in bounded spatial regions has been observed in several studies.[7–9] These facts agree with the predictions of the model proposed here, although they could apparently also be explained in other ways.

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