Giant-vortex state induced by negatives values of deGennes parameter in a mesoscopic square

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Giant-vortex state induced by negatives values of deGennes parameter in a mesoscopic square

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Abstract. Using different negatives values of deGennes parameter in the boundary condition of a square sample superconducting type II is possible to change its vorticity. Due to the proximity effects, the cooper pairs density snapshot show how a giant vortex occurs when the external magnetic field is increased. Solving numerically the coupled nonlinear time dependent Ginzburg-Landau equations we obtain the vorticity, magnetic induction, cooper pair density, magnetization and phase of the order parameter as a function of the external magnetic field for this sample. We found that a giant vortex state occurs when a sample is surrounded by another superconductor at higher critical temperature.

1. Introduction
The Ginzburg-Landau (GL) equations [1] are arguably the most convenient and frequently employed tool in studying of the vortex matter and thermodynamics properties of superconducting samples with general boundary condition. The size of the sample is usually considered to be large enough that the influence of finite dimensions on their properties is negligible; however, in many situations of interest, i.e. mesoscopic superconductivity, metallic nanoparticles [2, 3], microfluidics,[4, 5] the size effects are very important. Advances in engineering have been possible to enhance critical fields, critical temperature and critical currents to have a better control in the thermodynamic properties of superconducting samples. The possibility to control the dynamics and vortex density has made of this physics one of the favorite experimental and theoretical topic for studies of the solid state [6, 7, 8, 9, 10, 11]. In this paper, we solve the Ginzburg Landau equations for a mesoscopic square sample in presence of an external magnetic field applied perpendicular at its surface, we consider a superconducting/superconducting at higher critical temperature boundary conditions. We found that is possible to obtain a Giant-vortex state induced due to the presence of the another superconductor.
2. Theoretical Formalism

We considered a small superconducting square in the presence of a perpendicular uniform magnetic field \( H_e \). The general form of the time dependent Ginzburg-Landau equations is

\[
\frac{\partial \psi}{\partial t} = -(i \nabla + \vec{A})^2 \psi + \psi (1 - |\psi|^2) \\
\frac{\partial \vec{A}}{\partial t} = \text{Re} \left[ \psi (-i \nabla - \vec{A}) \psi \right] - \kappa^2 \nabla \times \nabla \times \vec{A}
\]

(1)  (2)

In Eqs. (1) and (2) dimensionless units were introduced as follows: \(|\psi|\) is the order parameter in units of \( \psi_\infty (0) = \sqrt{-\alpha (0)} / \beta \), where \( \alpha (0) \) and \( \beta \) are two phenomenological constants; lengths in units of the coherence length \( \xi (0) \); time in units of \( t_0 = \pi \hbar / 8 K_B T_c \); \( \vec{A} \) in units of \( H_e (0) \xi (0) \), where \( H_e (0) \) is the second critical field, temperature in units of the critical temperature \( T_c \), \( \lambda (0) \) is the penetration depth \( [12] \). We studied a mesoscopic superconducting square of size \( 3 \xi (0) \times 3 \xi (0) \) with a superconductor/superconducting at higher critical temperature external interface simulated by \( b / \xi (0) = -1.7 \), with \( \kappa = 5.0 \), \( T = 0 \), \( a_x = a_y = 0.125 \).

2.1. Numerical Method

The full discretization of the TDGL equations can be found in more detail in Ref. [13]. We used \( U \psi \) method [14] for solve the TDGL equations in a discrete grid. Complex link variables \( \mathcal{U}^x \) and \( \mathcal{U}^y \) are introduced to preserve the gauge-invariant properties of the discretized equations. \( \mathcal{U}^x \) and \( \mathcal{U}^y \) are related to \( \vec{A} \) by:

\[
\mathcal{U}^x (x, y, t) = \exp \left( -i \int_{x_0}^{x} A_x (\xi, y, t) \, d\xi \right) \Leftrightarrow \mathcal{U}^y (x, y, t) = \exp \left( -i \int_{y_0}^{y} A_y (x, \eta, t) \, d\eta \right)
\]

(3)

The link variable method is used since a better numerical convergence is obtain in high magnetic fields [15]. The TDGL equations 1 and 2 can be written in the following form:

\[
\frac{\partial \psi}{\partial t} = \mathcal{U}_x \frac{\partial^2 (\mathcal{U}_x \psi)}{\partial x^2} + \mathcal{U}_y \frac{\partial^2 (\mathcal{U}_y \psi)}{\partial y^2} + (1 - T) \psi (1 - |\psi|^2) \Leftrightarrow \mathbf{J}_{\text{sa}} = (1 - T) \text{Im} \left[ \mathcal{U}_x \overline{\psi} \frac{\partial (\mathcal{U}_x \psi)}{\partial \alpha} \right]
\]

(4)

where \( \alpha = (x, y) \), and \( \text{Im} \) indicates the imaginary part. We used this method to obtain our results. The outline of this simulation procedure is as follows: the sample is divided in a rectangular mesh consisting of \( N_x \times N_y = 36 \) cells, with mesh spacing \( a_x \times a_y = 0.5 \). To derive the discrete equations let us define by \( x_i = (i - 1) a_x, \quad y_i = (i - 1) a_y \), an arbitrary vertex point in the mesh and:

\[
U^x_{i,j} = \mathcal{U}^x_{i,j} \mathcal{U}^x_{i+1,j} = \exp \left( -i \int_{x_i}^{x_{i+1}} A_x (\xi, y_i) \, d\xi \right) \Leftrightarrow U^y_{i,j} = \exp \left( -i \int_{y_j}^{y_{j+1}} A_y (x_i, \eta) \, d\eta \right)
\]

\[
L_{i,j} = U^x_{i,j} U^y_{i+1,j} \bar{U}^x_{i+1,j} \bar{U}^y_{i,j} = \exp (-ia_x a_y H_e)
\]

Then the discretized version of the TDGL equations maintaining second order accuracy in space are given by:

\[
\frac{\partial \psi_{i,j}}{\partial t} = \frac{U^x_{i,j} \psi_{i,j} - 2 \psi_{i,j} + U^x_{i-1,j} \psi_{i-1,j} + U^y_{i,j} \psi_{i,j+1} - 2 \psi_{i,j} + U^y_{i,j-1} \psi_{i,j-1}}{\eta \alpha_x^2} - \frac{1 - T}{\eta} (\bar{\psi}_{i,j} \psi_{i,j-1}) \psi_{i,j}
\]

\[
\frac{\partial U^x_{i,j}}{\partial t} = -i (1 - T) U^x_{i,j} \text{Im} \left( \bar{\psi}_{i,j} U^x_{i,j} \psi_{i,j+1} \right) - \frac{\kappa^2}{a_x^2} U^x_{i,j} (L_{i,j-1} L_{i,j} - 1)
\]

\[
\frac{\partial U^y_{i,j}}{\partial t} = -i (1 - T) U^y_{i,j} \text{Im} \left( \bar{\psi}_{i,j} U^y_{i,j} \psi_{i,j+1} \right) - \frac{\kappa^2}{a_y^2} U^y_{i,j} (L_{i,j} L_{i-1,j} - 1)
\]
3. Results and Discussion

Fig. 1 a). We present the magnetization as a function of the external magnetic field $H_e$ for a mesoscopic superconducting square of size $3\xi(0) \times 3\xi(0)$ with a superconductor/superconducting at higher critical temperature external interface. These curves present a typical profile of a magnetization curve of a mesoscopic superconductor. It exhibits a series of discontinuities, in which each jump signals the entrance of vortices into the sample.

Fig. 1 b). We have vortex transition from $N$ to $N+1$ in part of the upward branch of the magnetic field. The magnetic field for vortices entries are $H_e/H_c^2(0) = 2.608$, $3.618$, $4.478$, $5.219$ and $6.027$ with $N = 1, 2, 3, 4, 5, 6$ for using $b/\xi(0) = -1.7$ and inset the cooper pairs density snapshot show how a giant vortex occurs when the external magnetic field is increased as we can see the order parameter which is mostly $\Psi = 0$ in the sample (blue region) and this condition allows the penetration of vortices and the number of vortices can be determined in a given region, by counting the number of fluxoid variation.

Fig. 2 we shown the contour plot of the the magnetic induction and the phase of order parameter for three negatives values of deGennes parameter $b/\xi(0) = \infty, -2.5, -12.5$, for mesoscopic sample with $3\xi(0) \times 3\xi(0)$ dimension. Following the panels from the left to the right, in this order, it shown that is possible to obtain a giant-vortex configuration. That is why, although the vorticity grows from $N = 1$ to $N = 3$, as we can see in the phase of order parameter which changes from dark (red) to bright (blue) regions represent values of the modulus of the order parameter (as well as $\Delta \phi/2\pi$, changes from 0 to 1). The color code for values of the phase close to zero are given by dark (red) regions and close to $2\pi$ by light (blue) regions. Despite the vortices are indistinguishable in the contour plot of the magnetic field induction, leading to the formation of the giant vortex. This kind of vortex can be achieved if the deGennes parameter values and applied magnetic field harmonize for every giant-vortex state in this high confinement system.

4. Conclusions

We studied the effect of the different negative values of the deGennes parameter ($b$) in the thermodynamics properties for a small superconducting square of size $3\xi(0) \times 3\xi(0)$ in presence of a magnetic field is investigated theoretically, simulating this sample with boundary conditions.
in which its lateral surface has a superconducting/superconducting at higher critical temperature by solving the coupled nonlinear Ginzburg-Landau equations. Our results shown that the giant-vortex state and their principal characteristics such as magnetic induction, cooper pair density, magnetization and the phase of order parameter depend strongly of the chosen boundary condition and the applied magnetic field.

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