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Study of the threshold line between macroscopic and bulk behaviors for homogeneous type II superconductors

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ABSTRACT

In this work we solved the time dependent Ginzburg–Landau equations to simulate homogeneous superconducting samples with square geometry for several lateral sizes. As a result of such simulations we notice that in the Meissner state, when the vortices do not penetrate the superconductor, the response of small samples are not coincident with that expected for the bulk ones, i.e., $4\pi M = -H$. Thus, we focused our analyzes on the way which the $M(H)$ curves approximate from the characteristic curve of bulk superconductors. With such study, we built a diagram of the size of the sample as a function of the temperature which indicates a threshold line between macroscopic and bulk behaviors.

1. Introduction

The advances in nanofabrication techniques which occurred on the last decades stimulated the production and, consequently, experimental and theoretical studies of superconducting samples with sizes of the order of their fundamental lengths, i.e., $\lambda(T)$ and $\xi(T)$. In such materials the superconducting properties and the vortex dynamics are hugely affected by confinement effects. As a consequence, multi and giant vortex states takes place [1–20] as well as the coexistence of vortex and antivortex pairs.[6] Such systems also present others exotic behaviors as non-quantized vortex penetration [21] and the arrangement of the vortex lattice in several geometries which follow the symmetry of the samples [1,4,8,22–31].

Recently, theoretical studies with mesoscopic superconductors of type I shown that an applied current in a slab induced the penetration and annihilation of single quantized vortex in the intermediate state [32]. The confinement effects can also induced the suppression of the intermediate state and drastically changed the size and temperature dependence of the critical fields of such materials [33].

It is interesting to note that, in all cited works, the mesoscopic superconductors are treated, generically, as materials of reduced dimensions of the order of $\lambda(T)$ or $\xi(T)$. However, no much attention is done on the real sizes for which a sample could be defined as a mesoscopic specimen. Thus, it is worth to emphasize that the knowledge of the relation between size and superconducting behavior is very important to guide the researchers in their theoretical and experimental studies. Recently, Connolly et al. [34] published a work where they used a criterion based on the competition between the Abrikosov vortex lattice and a shell-like ordering to define a meso-to-macroscopic crossover of a superconducting disk. With the same purpose, the authors of the Ref. [26] proposed the existence of a threshold line between mesoscopic and macroscopic superconducting behaviors. For the mesoscopic-like behavior, the confinement effects are strong enough to induce a crossover of the the vortex lattice and the vortices arrangement follows the symmetry of the sample. Nevertheless, the macroscopic behavior is mainly characterized by some volumetric properties like the value of the upper critical field $H_{c2}(T)$ and the presence of the hexagonal vortex lattice. However, in this state the outer vortices are influenced by the surface and are arranged in a kind of shell.

A possible question that should arise from such analysis is about the typical sizes for which the surface effects could be neglected. Thus, in the present work we determined a possible threshold line between the macroscopic and bulk behaviors. This last one have been defined as the samples for which the influence of the surface on the vortex dynamics could be neglect. In this way, the outline of our work is as follow. First, in Section 2, we provide an overview of the theoretical formalism used to run the simulations. Next, in Section 3 we describe some definitions used in this paper and an overview of a previous work which was the motivation for the present one. In the remainder Sections 4 and 5 we dis-

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cuss our results and the criteria used to obtain the crossover line between macro-to-bulk behaviors and present our conclusions.

2. Theoretical formalism

The phenomenological theory developed by Ginzburg and Landau (GL for short) [35] is a very important tool to study the behavior of type I and type II superconductors. In such theory, the superconducting state is described by a complex order parameter ψ, for which the physical quantity $|\psi|^2$ represents the density of superconducting carriers, i.e., the Cooper pairs, and the vector potential $\mathbf{A}$ which is related with the local magnetic field by $\mathbf{h} = \nabla \times \mathbf{A}$. The Ginzburg–Landau equations in their time-dependent form are expressed by [36]

$$\left(\frac{\partial}{\partial t} + i\Phi\right)\psi = -(-i\nabla - \mathbf{A})^2\psi + (1 - T)\psi(1 - |\psi|^2),$$

$$\beta\left(\frac{\partial \mathbf{A}}{\partial t} + \nabla\Phi\right) = \mathbf{J}_s - \kappa^2\nabla \times \mathbf{h}, \qquad (1)$$

where $\mathbf{J}_s = (1 - T)\Re[\psi^*(-i\nabla - \mathbf{A})\psi]$ is the supercurrent density, and Φ is the scalar potential; these two equations are commonly referred to as time dependent Ginzburg–Landau equations (TDGL for short). Thus, the time evolution of a superconducting system and, consequently, the evolution of the vortices even in non-stationary states, could be followed. However, for our purposes, we will use the TDGL equations just as a relaxation method to achieve the stationary state. This is only a matter of convenience, since we could solve the GL equations by other means. For example, we could solve then by finite elements methods (see for instance Ref. [37].

Here, the distances are measured in units of the coherence length at zero temperature $\xi(0)$; the magnetic field is in units of the zero temperature upper critical field $H_{c2}(0)$; the temperature T is in units of the critical temperature T_c; the time is in units of the characteristic time $t_0 = \pi\hbar/8k_BT_c$; κ is the Ginzburg–Landau parameter; β is the relaxation time of $\mathbf{A}$, related to the conductivity. Rigorously speaking, the Ginzburg–Landau theory is applicable only for temperatures close to T_c. However, as we are interested in a general feature of a threshold line between macro-to-bulk superconducting behaviors, we have adopted a linear dependence with respect to the temperature for the phenomenological parameters in the Ginzburg–Landau theory, i.e., $H_{c2}(T) = H_{c2}(0)(1 - T)$.[1] It is interesting to emphasize that the Ginzburg-Landau theory was proven to give good qualitative results in mesoscopic superconductors even at low temperature, despite the microscopic derivation of the Ginzburg-Landau equations being valid only for T very close to T_c [38,39]. For better quantitative comparisons at low temperatures, one should employ Boguliobov-deGenes [42–47], Eilenberger [48–52], or recently developed Extended GL model [53].

In this work we solved the TDGL equations for very long cylinders of square cross section and with several lateral sizes, expressed by $L/\xi(0)$, as described in references [26,31]. Those equations were discretized following the link variables method as developed by Gropp and coworkers [40]. It is interesting to emphasize that the TDGL equations, even in their discretized form, are gauge invariant under the transformations $\psi' = \psi e^{i\chi}$, $\mathbf{A}' = \mathbf{A} + \nabla\chi$, $\Phi' = \Phi - \partial\chi/\partial t$, where ψ is the order parameter, $\mathbf{A}$ is the vector potential, Φ is the scalar potential and χ is a scalar function. In this study we chose the zero-scalar potential gauge, that is, $\Phi' = 0$, at all times and positions.

The simulations were carried out for a type II superconductor with $\kappa = 5$, and we focused the analyzes on the Meissner state, i.e., the region of small intensities of magnetic fields which were applied along the cylinder axis. The field was incremented in steps of $\Delta H = 10^{-3}$. Although the TDGL equations can provide all the metastable states of a fixed field, as stressed previously, in the present work we studied only the stationary states. We used the value of $\beta = 1$. This choice has no influence on the final configuration of the stationary state since it affects only the time steps to achieve the steady state [41].

3. Crossover Criteria

In order to facilitate the discussion of our results, in this work we have used the following terminology. First, by *mesoscopic* we mean a superconductor of dimensions such that the vortex lattice is mostly influenced by the geometry of the sample. In addition, in the mixed state, the magnetization is not a smooth function of the applied field; it has a series of jumps which indicate the nucleation of one or more vortices. Second, according to references [26,31], as the size of the sample is increased, there is a length scale above which deep inside the superconductor, the vortex lattice is not perturbed by the surface effects, although they are still present. In this regime, which we denote by *macroscopic*, the vortices are arranged nearly as a triangular lattice, except near the surface where there are some distortions. Also, in the mixed state, the height of the jumps in the magnetization curves are very small so that it approaches to a continuous line. Finally, by *bulk* superconductors we mean those with an infinite size such that the vortex configuration is a perfect triangular lattice through the whole sample. In other words, an ideal superconductor for which all surface effects are suppressed.

Recently, by solving the TDGL equations for many dimensions of a square and many temperatures, the authors of reference [26] developed a work where they built a diagram of the size of square superconducting samples versus the temperature, $L_c(T)$, as shown in the inset of Fig. 1. This diagram delimits two distinct behaviors of type II superconductors, i.e., they have shown the existence of a threshold line between mesoscopic and macroscopic superconducting behaviors. This curve is quite different of the penetration depth of the material, $\lambda(T)$, which is commonly used as the definition for the typical size of mesoscopic samples. Thus, the curve $L_c(T)$ represents the *meso-to-macro crossover*, that is, a length which

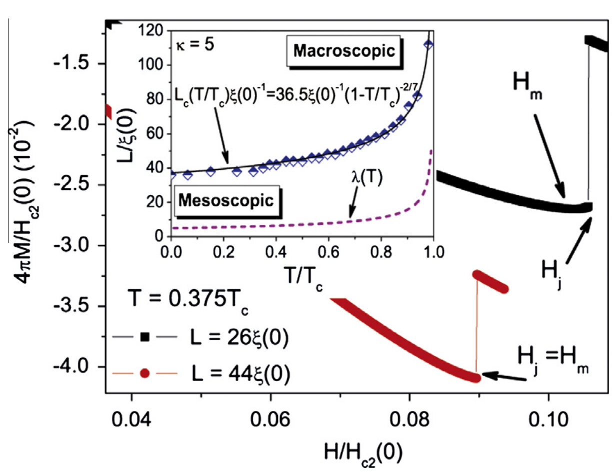

Fig. 1. Magnetization versus applied magnetic field curve for superconducting squares of sizes $L = 26\xi(0)$ and $44\xi(0)$ at $T = 0.375T_c$. As $L/\xi(0)$ increases, H_j and H_m become close one each other and when they are coincident the corresponding size is chosen as the threshold point between meso-to-macro behaviors for such temperature. The inset shows the $L_c(T)/\xi(0)$ diagram in comparison with $\lambda(T)$.

[1] We have chosen the simplest model for the temperature dependence of the physical quantities. Other better choices which are valid for T well below the critical temperature do not invalidate the present investigation, since our main aim is to show that there is a length scale for which we have a meso-to-bulk crossover, no matter what is temperature dependence of $H_{c2}(T)$.