Journal of Low Temperature Physics, Vol. 135, Nos. 1/2, April 2004 (© 2004)

Amorphous vortex phase in $Bi_2Sr_2CaCu_2O_8$ after the first order liquid-solid phase transition

M. Menghini[1],Yanina Fasano[1], F. de la Cruz[1], S.S. Banerjee[2], Y. Myasoedov[2], E. Zeldov[2], C. J. van der Beek[3], M. Konczykowski[3] and T. Tamegai[4]

[1]*Instituto Balseiro and Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, Bariloche, Argentina*
[2]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel*
[3]*Laboratoire des Solides Irradiés, CNRS UMR 7642, Ècole Polytechnique, Palaiseau, France*
[4]*Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo and CREST Japan Science and Technology Corporation (JST), Japan*

It is widely accepted that the first-order vortex liquid-solid phase transition is associated with a crystalline solid phase and the second order transition with an amorphous one. The combination of a technique that determines the order of the transition with the visualization of the vortex structure has allowed the detection, for the first time, of a first-order liquid-solid transition without structural symmetry change. The results show that the quasi-long range order of the solid phase is not a necessary condition for the first-order phase transition to occur. This opens an important question on the microscopic origin of the liquid-solid phase transition in vortex matter.

PACS numbers: 74.25 Qt, 74.25 Bt, 74.25 Op, 74.72 Hs

Usually first-order liquid-solid transitions (FOT) are associated with a topological transformation from a disordered state to a crystalline structure. It is well accepted that the vortex liquid in the presence of atomic quenched disorder solidifies through a FOT [1] into a phase of hexagonal symmetry with quasi-long range order and local elastic deformations, the Bragg Glass [2].

High energy heavy ion irradiation generates columnar defects (CDs) that have a drastic influence [3] on the thermodynamics of vortex matter. The density of CDs, n_{col}, is associated with a matching field $B_\Phi = n_{col}\Phi_0$, where

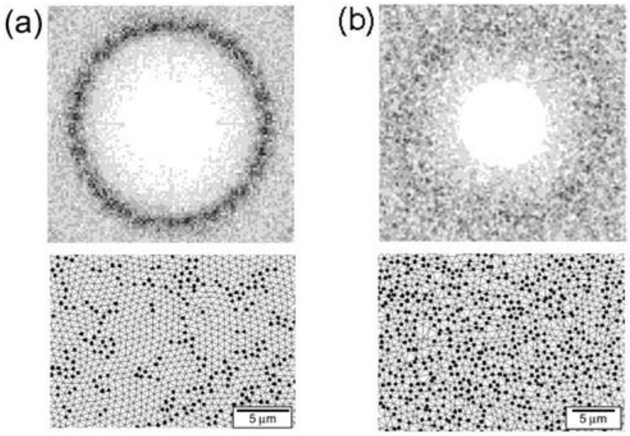

Fig. 1. Fourier Transform (upper panel) and Delaunay Triangulation (lower panel) of the vortex structure for (a) 30 G in the $B_\Phi = 5$ G and (b) 30 G in the $B_\Phi = 50$ G sample. The black dots in the triangulations depict the topological defects of the vortex structure.

Φ_0 is the flux quantum. It has been widely accepted that the presence of CDs transforms the FOT into a second order one (SOT), where the solid has no topological long range order, the Bose Glass [3]. However, recent studies [4,5] of the phase diagram in $Bi_2Sr_2CaCu_2O_8$ (BSCCO-2212) show that the FOT is robust in the presence of a low density of CDs. The aim of this work is to study the vortex topology in the presence of CDs and its relationship with the thermodynamic order of the liquid-solid phase transition.

Field cooling (FC) magnetic decorations show that the vortex structure of irradiated samples is topologically disordered, see Fig. 1 (a) and (b) upper panel. The analysis of the vortex structure in real space indicates that the vortices form a polycrystal in the regime $B > B_\Phi$, as clearly observed in the Delaunay triangulation (Fig. 1(a) lower panel). A detailed analysis of the polycrystalline structure shows that there is a homogeneous distribution of grain size with minimum and maximum values for each B. The main result of this analysis is that the number of vortices within the smallest and the largest grains is proportional to B [6]. This implies that the grains size and its statistical distribution are B independent. The invariance of the grain size in the irradiated samples as a function of B is in contrast with the observed [7] enlargement of crystalline domains with B associated with nucleation and growth processes. This strongly supports that the grain size as well as the

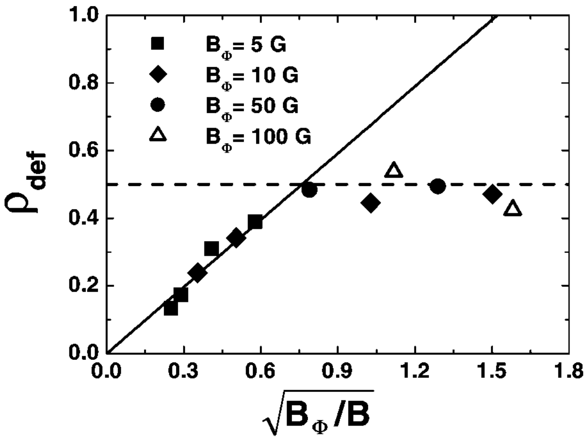

Fig. 2. Fraction of defects, ρ_{def}, as a function of $(B_\Phi/B)^{1/2}$. The solid line corresponds to $\rho_{def} \propto (B_\Phi/B)^{1/2}$ and the dotted line to $\rho_{def} = 0.5$.

space distribution of the grains are determined by the CDs landscape.

The inhomogeneous distribution of CDs on the scale of average vortex distance, a_0, is compatible with the presence of vortex contours induced by CDs resembling the grain boundaries of the polycrystalline vortex structure where most of the topological defects (non-sixfold coordinated vortices) are located [6]. This allows us to propose a model to describe the behavior of the fraction of topological defects of the vortex structure, ρ_{def}, as a function of B and B_Φ. We assume $N_{def} \propto N_{cont}$, where N_{def} is the number of topological defects and N_{cont} is the number of vortices on the contours in a given area A. Since the total length of the contours can be written as $L = N_{cont}a_0$ and since the area of the grains is independent of B, L becomes a function only of B_Φ. Then, $N_{def} \propto N_{cont} \propto L(B_\Phi)B^{1/2}$. Since the area of the grains scales as $1/B_\Phi$, $L(B_\Phi) \propto B_\Phi^{1/2}$ and $\rho_{def} = N_{def}/N_v \propto (B_\Phi/B)^{1/2}$. [6] The experimental values of ρ_{def} in samples with $B_\Phi = 5, 10, 50$ and 100 G are depicted in Fig. 2. The agreement with the model based on the existence of contours in the regime $B > B_\Phi$ is evident. In the limit $B < B_\Phi$ most of the contours induced by CDs enclose areas that are too small to be filled by enough vortices to form crystallites. This explains the detected deviation of the experimental results from the square root behavior predicted by the model, as shown in Fig. 2. This is consistent with the amorphous vortex structure obtained by FC decorations for $B < B_\Phi$, see Fig. 1 (b). Moreover, we found that a random distribution of vortices with the constraint that the distance between two of them is greater than $0.5a_0$ has approximately the same fraction of topological defects as the structure observed in this regime, $\rho_{def} \approx 0.5$.

The amorphous vortex structure obtained in the regime $B < B_\Phi$ in the sample with $B_\Phi = 50$ G reveals an uncommon result in nature: A melting of an amorphous solid through a first-order phase transition. This result indicates that, even though no crystallites are formed within the contours, the solidification of the vortex liquid is characterized by a finite step in the magnetization.

In conclusion, the analysis of the vortex structure as a function of CDs density shows that the structure of the solid phase is determined by CDs random distribution that induces contours of pinned vortices. These contours confine regions where the rest of the vortices have to be fitted, giving support to the recently suggested porous vortex matter. Based on the existence of these contours, we have shown that the fraction of topological defects of the vortex structure can be well described by a simple model. Moreover, the results show that the first-order liquid-solid transition in vortex matter does not require the widely accepted long range topological order of the solid state [6,8]

ACKNOWLEDGMENTS

Partially supported by ANPCYT Argentina, Fund. Antorchas-WIS Collaboration Program and the Israel Science Foundation Center of Excellence.

REFERENCES

1. H. Safar *et al.*, Phys. Rev. Lett. **69**, 824 (1992). H. Pastoriza *et al.*, Phys. Rev. Lett. **72**, 2951 (1994). E. Zeldov *et al.*, Nature **375**, 373 (1995).
2. T. Giamarchi and P. Le Doussal, Phys. Rev B **52**, 1242 (1995).
3. D. R. Nelson and V. M. Vinokur, Phys. Rev. B **48**, 13 060 (1993).
4. B. Khaykovich *et al.*, Phys. Rev. B **57**, R14 088 (1998).
5. S. S. Banerjee *et al.*, Phys. Rev. Lett. **90** 087004 (2003).
6. M. Menghini *et al.*, Phys. Rev. Lett. **90** 147001 (2003).
7. M. V. Marchevsky Ph.D. Thesis, Kamerlingh Onnes Laboratory, Leiden University, Holland.
8. S. Colson *et al.*, Phys. Rev. Lett. **90** 137002 (2003).