Order-disorder transition of vortex matter in Mg$_{0.9}$B$_{2}$: anisotropic effects

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Abstract. Third-harmonic susceptibility studies have been employed to probe the order-disorder transition of Vortex Matter of a magnesium-deficient sample of MgB$_2$. Our results reveal that the measured threshold is anisotropic for different orientations of the applied magnetic field, suggesting that the pinning efficiency of the magnesium-deficient regions depend on the orientation of the penetrated vortices.

1. Introduction

For a type II superconductor in its mixed state the magnetic flux penetrates into the material as quantized vortices, which combine to form the Vortex Matter (VM). The number of quantized vortices increases with the external dc magnetic field, $H$, and in a clean superconductor the competition between the intervortex repulsion and the magnetic pressure from the outside field causes the vortices to arrange themselves in a regular ordered state, the Abrikosov lattice. However, real superconductors have defects, such as grain boundaries, voids, inhomogeneities, twin planes, point and columnar defects – which pin the vortices, and prevent them from moving, breaking the Abrikosov lattice. In general, depending on the nature and amount of defects existent in the studied material, the ordered state of VM can be modified, from a quasi-ordered vortex lattice, or Bragg glass [1], when the density of defects is low, to a vortex-glass state [2], if uncorrelated pinning centers (PCs), like disorder and impurities, are present, and lastly, to a Bose glass [3], in the presence of correlated disorder, like columnar defects (CDs).

In single crystals of MgB$_2$, VM tends to form a quasi-ordered vortex structure at low dc magnetic fields [4], i.e., the magnetic field versus temperature (HT) phase diagram of a clean MgB$_2$ specimen has a region where the stable vortex phase is the Bragg glass [1]. Nonetheless, by tuning the amount of quenched random point-like disorder, the stabilization of a highly disordered phase can be favored and, consequently, an order-disorder (OD) transition, $H_{OD}(T)$, in fields below the upper critical field, $H_{c2}(T)$, should become observable in the mixed phase of MgB$_2$ with random disorder. In this contribution, we have employed the third harmonic of the AC susceptibility technique [5] to determine the OD line of a good-quality sample of Mg$_{0.9}$B$_2$ [6] with a random amount of defects, corresponding to Mg-deficient regions.
2. Samples and experimental method

The polycrystalline sample of Mg_{0.9}B_{2} employed in this study was prepared by solid state reaction methods under high pressure, details of which were given in Ref. [6]. Noticeably, it is possible to recognize that the studied sample has a growth preferential direction (GPD). All results presented in this section were obtained with H perpendicular to GPD.

To probe the occurrence of the OD transition of VM in Mg_{0.9}B_{2}, we employed the third-harmonic susceptibility, \( \chi_3 \), method. It is based on the fact that, at the OD threshold, the magnetic response of the system changes from non-linear (ordered regime), \( \chi_3 \neq 0 \), to linear (disordered regime), \( \chi_3 = 0 \).

Experimentally, the OD line on the HT plane was constructed through measurements of the temperature dependence of \( \chi_3 \) in the presence of dc magnetic fields. Measurements of \( \chi_3(T) \) were conducted using the AC module of a PPMS (Physical Properties Measurements System, Model 6000) Magnetometer by Quantum Design. In figure 1, we show the temperature dependence of the amplitude of the first, \( \chi_1 = |\chi_1'| + i|\chi_1''| \), and third, \( \chi_3 = |\chi_3'| + i|\chi_3''| \), harmonics of the AC-susceptibility, taken with the amplitude, \( h \), and frequency, \( f \), of the excitation field fixed at 70 mOe and 100 Hz, respectively, in the presence of a dc field of 2 T. One can clearly observe that the onset temperature of \( \chi_3, T_3^{\text{onset}} \), is lower than \( T_1^{\text{onset}} \), the onset temperature of \( \chi_1 \), indicating the existence of an interval temperature, \( T_3^{\text{onset}} < T < T_1^{\text{onset}} \), where the magnetic response is linear. Here, \( T_1^{\text{onset}} = T_c \) is the critical temperature of the sample.

![Figure 1. Temperature dependence of \( \chi_1 \) and \( \chi_3 \). The experimental parameters were: \( h = 70 \) mOe, \( f = 100 \) Hz, and \( H = 2 \) T. Note that the lower portion of the graph, demarcated by the hachured rectangle, represents the noise level associated to the measurements. For each curve, the last point belonging to this noise range was labelled \( T_1^{\text{onset}} \) and \( T_3^{\text{onset}} \).](image-url)

The dependence of \( T_3^{\text{onset}} \) and \( T_1^{\text{onset}} \) with the experimental parameters \( h \) and \( f \) is shown in figures 2(a) and 2(b), respectively. In both figures, it should be noticed that while \( T_1^{\text{onset}} \) stays approximately fixed at \((30.6 \pm 0.4) \) K, \( T_3^{\text{onset}} \) changes from that value to an other constant, \((27.2 \pm 0.4) \) K for \( h \leq 70 \) mOe, figure 2(a), and \((27.3 \pm 0.4) \) K for \( f \leq 100 \) Hz, figure 2(b). Taking into account such behaviors, it is evident that for \( h \leq 70 \) mOe and \( f \leq 100 \) Hz, the OD threshold is free from spurious contributions related to experimental parameters, i.e., \( T_3^{\text{onset}}(H) \) is independent of \( h \) and \( f \). The results presented in the remainder of this paper were obtained with \( h = 70 \) mOe and \( f = 100 \) Hz.
3. Results and discussion

It is known that the crystalline structure and the electronic and phononic band structures [7] of MgB$_2$ are far from being regarded as isotropic, and thus should lead to anisotropic superconducting properties. For instance, we point out the anisotropy in $H_{c2}(T)$ detected on polycrystalline samples [8], thin films [9] and single crystals [10]. Conversely, few studies about anisotropic effects in the mixed state of such compound have been accomplished [11]. In this section we investigate the anisotropy exhibited by the OD transition.

Figure 2. Dependence of $T_{1 \text{onset}}$ and $T_{3 \text{onset}}$ with $h$ (a) and $f$ (b). For the study of the amplitude (frequency) dependence, $h$ ($f$) and $H$ were maintained fixed at 70 mOe (100 Hz) and 2 T.

Figure 3. Order-disorder transitions of VM in Mg$_{0.9}$B$_2$. In the legend, the $H$ // GPD and $H$ $\perp$ GPD terms denote that $H$ was applied parallel and perpendicular to GPD, respectively.

Figure 3 shows the $H_{\text{OD}}(T)$ frontiers, for the Mg$_{0.9}$B$_2$ sample, obtained with $H$ in two different orientations: parallel and perpendicular to GPD. Notice that for low values of $H$ both contours coincide. However, for higher fields, $H_{\text{OD}}(T)$ is lower for $H$ parallel to GPD, indicating that in such configuration, the magnetic response is linear in a broader range of temperatures. This notable enlargement of the disordered phase of VM could be explained if the efficiency of PCs for the parallel geometry were smaller than for perpendicular. In order, to verify this, we calculated the pinning force density, $F_p = J \times B$, for both geometries.

The current density, $J$, was computed from magnetization loops, $M(H)$, by Bean’s critical state model [12], $J_c = (30 \Delta M/r) A/cm^2$, where $\Delta M$ is the height of the loop, and $r$ is the dimension of the sample perpendicular to the field direction. Figure 4 shows the field dependence of $F_p$, at 30 K. It can
be noticed that in the parallel geometry, $F_{p//}$ assumes values smaller than $F_{p\perp}$ (referent to the perpendicular geometry), for the entire field interval. Therefore, this result reveals a smaller pinning efficiency of the magnetic flux by PCs when $H$ is applied parallel to GPD.

It is worth mentioning that the difference between the $H_{OD}(T)$ lines for both orientations (figure 3) disappears if the vertical axis is rescaled by a characteristic length, $l$, associated with the density of defects (deficient sites) along the direction of the field. A more detailed discussion about this subject will appear elsewhere.

![Figure 4. Dependence of $F_p$ with $H$ at 30 K.](image)

4. Final remarks

We have employed the third harmonic of the AC-susceptibility to determine the order-disorder transition of Vortex Matter of a good-quality sample of Mg$_{1-x}$B$_2$, whose amount of defects was tuned through control of the magnesium content ($x = 0.1$). It is found that, depending on the orientation of the applied magnetic field, the pinning efficiency of the magnesium-deficient regions can be strongly increased, shifting, thus, the OD contour for higher values of the magnetic field.

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