Transition between the Bragg glass and the disordered phase in Nb_3Sn detected by third harmonics of the ac magnetic susceptibility

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We report on experimental evidence of the presence of a universal behavior in the field-temperature phase diagram of type II superconductors, characterized by a phase transition in the vortex matter between the disordered and the Bragg glass phase. The experimental detection of a peak effect phenomenon has been proved to be strictly connected to the existence of this phase transition. In this paper, we show an observation of a peak effect in the compound Nb_3Sn, by using first harmonics of the ac magnetic susceptibility. Peak effect has been detected at fields between 3 and 13 T, whereas it is not observable at higher fields. This seems to be in contrast with the theoretical predictions of such a phase transition at all fields and, therefore, with the predicted universality in the magnetic behavior of the type II superconductors. Nevertheless, by measuring the third harmonics of the ac susceptibility, this phase transition has been detected up to our highest available field (19 T), thus demonstrating the necessity of the higher harmonics analysis in studying these topics and moreover proving the validity of the theoretical predictions.

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Magnetic flux penetrates a type II superconductor in the form of vortices, which distribute in a regular lattice in the absence of defects.[1,2] Defects affect the lattice ordering, but prevent the dissipations associated to the vortex movement.[2] A universal field-temperature phase diagram has been supposed for all the type II superconductors with point defects. In this phase diagram, a transition in the vortex lattice has been predicted between a disordered phase and the Bragg glass phase.[3,4] This latter is characterized by a quasi-long-range order and a perfect topological order, in which the vortex lattice still survives despite the presence of the pinning,[3] as has also been experimentally evidenced.[5] The disordered phase has been supposed to be again a glass phase ("multidomain glass"), but with a topological disorder at the largest length scales.[4] The critical current density, J_c,[6] generally decreasing with increasing temperature and/or magnetic field,[2] shows a local maximum, known as the peak effect,[7] when the disordered/Bragg phase transition occurs. For this reason, the observation of the peak effect has been widely used to detect this phase transition.[3] The peak effect has been evidenced in various classes of type II superconductors, e.g., low-T_c,[8–12] high-T_c,[13–15] boro-carbides,[16] and MgB_2.[17] However, it has not been observed in Nb_3Sn up to the present day, to the best of our knowledge.

Nb_3Sn crystallizes in the A15 type structure and is actually the most used material in the manufacturing of superconducting magnets at very high fields.[18] In the present work, measurements have been performed on a high-quality Nb_3Sn single crystal, furnished by Toyota[19] (Dimensions $\approx 3\times 1.32\times 0.43$ mm^3). The sample was characterized by $T_c=18.2$ K, $\Delta T_c=0.1$ K, $T_m=38.84$ K. A value of $H_{c2}(0)=22.2$ T was extrapolated using the Ginzburg-Landau-Abrikosov-Gorkov (GLAG) theory.[20]

The peak effect measurements reported in the literature were performed using various experimental techniques.[7,10,21–25] The technique used in the present paper is based on the observation of a dip in the real part of the first harmonics of the ac magnetic susceptibility, χ_1'.[23] The χ_1' dip indicates that the capability of superconductors to exclude the magnetic flux is nonmonotonic with the temperature. From the Bean critical state model,[6] it follows that the dip is directly related to a peak in J_c. Measurements of the harmonics of the ac susceptibility (χ_{ac}) have been widely used to study magnetic properties,[2,23,24,26,27] and in particular the vortex dynamics[27] in type II superconductors. If the magnetic response is linear, only the first harmonics can be detected, whereas nonlinear magnetic properties are associated with the existence of higher harmonics.[6,27] In this work, we used the measurements of third harmonics to investigate the phase transition between the disordered and the Bragg glass phase. This technique allowed us to extend the detection of this phase transition to considerably high fields, being only limited by the available field, 19 T.

In our experiments, a home-made susceptometer has been used to measure both first and third harmonics of χ_{ac} as a function of temperature, at dc magnetic fields up to 19 T, parallel to the ac field, approximately parallel to the longer dimension of the sample. Measurements have been performed at fixed frequency ($\nu=107$ Hz) and amplitude ($h_{ac}=128$ Oe) of the ac magnetic field.

In Fig. 1, evidence of the peak effect is shown, based on the real part of the first harmonics, $\chi_1'(T)$. Three different behaviors can be distinguished as a function of the dc magnetic field:

(a) $0\leqslant H<3$ T: the superconducting transition widens with increasing fields, and no dip has been evidenced in the real part of the first harmonics.

(b) $3\leqslant H\leqslant 13$ T: a dip can be observed, which becomes more pronounced up to $H=7$ T, its height decreasing for higher fields.

(c) $H>13$ T: above 13 T, the peak effect cannot be detected anymore in the first harmonic measurements; the su-

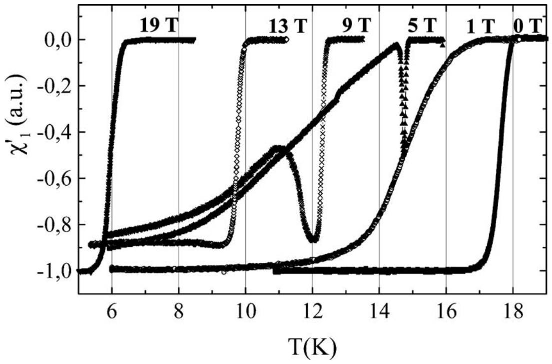

FIG. 1. Detection of the peak effect from the real part of the first harmonics of the ac magnetic susceptibility, χ_1', as a function of the temperature, T, at various dc magnetic fields. The peak effect has only been observed in the field range between 3 and 13 T.

perconducting transition is sharper than in (a).

The corresponding H-T phase diagram (shown in Fig. 2) has been obtained by plotting the critical temperature (T_c) and the peak temperature (T_p), i.e., the temperature corresponding to the local minimum in the dip, at various dc magnetic fields. In the H-T region below the T_p line, the vortex lattice still survives (Bragg glass),[3,5] whereas the disorder destroys the lattice in the temperature range between T_p and T_c.

It can be seen that the T_p line stops at a certain point in the high-field/low-temperature region of the phase diagram. This indicates that the observation of the disordered/Bragg glass phase transition by means of first harmonic measurements is limited to an intermediate-field/temperature region. A very similar behavior was reported earlier in the V_3Si system,[25] another A15 type compound: the Bragg glass phase extends without a transition up to the vortex liquid state, for high magnetic fields ($H > 7$ T). Nevertheless, the theoretical models[3] predict that this transition should be present, even at higher magnetic fields.

For the sake of clarity, in Fig. 2 we did not show the onset dip temperature (T_{pOn}),[24,31] being not associated with a thermodynamic transition.[29] Nevertheless, it remains an open question whether the region between T_p and T_{pOn} is due either to the introduction of the vortex disorder at the sample edges[30,32] or to a real coexistence of the two vortex phases, originated by superheating or supercooling phenomena.[31]

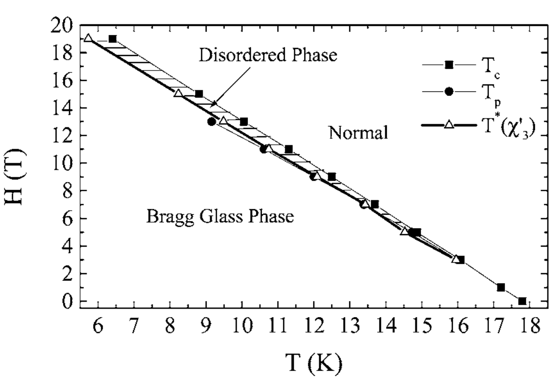

FIG. 2. H-T phase diagram from first and third harmonic measurements, obtained by plotting the critical temperature, T_c, and the peak temperature, T_p, extracted from the $\chi_1'(T)$ curves and $T^*(\chi_3')$, associated to the peak effect, in the real part of the third harmonics (see Fig. 3). We identified this latter line as the phase transition between the Bragg glass and the disordered phase.

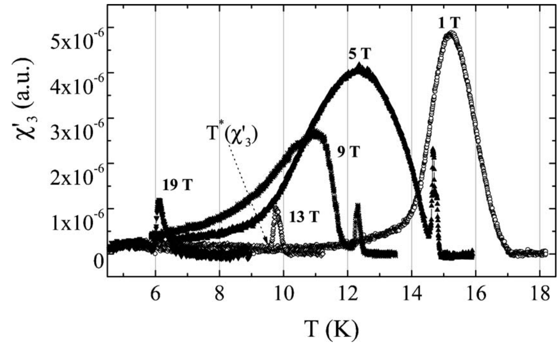

FIG. 3. Real part of the third harmonics as a function of temperature, at various dc magnetic fields.

By magnetic measurements, we have no information about the order of the transition. We detected magnetic history effects (which will be reported elsewhere) for temperature lower than the peak temperature (T_p), as in other type II superconductors,[24,25,28] but they are not proof of a first-order transition. Recent calorimetric measurements,[29] in fact, show that the latent heat is zero around T_p, suggesting that it cannot be a first-order transition.

By means of third harmonic measurements, it was possible to detect the disordered/Bragg glass phase transition even at higher magnetic fields, this verifying the theoretical predictions of Ref. 3. The real part of the third harmonics, as a function of temperature, $\chi_3'(T)$, is shown in Fig. 3 for various magnetic fields. At low fields ($H < 3$ T), where a dip was not observed in $\chi_1'(T)$, the data are in qualitative agreement with those obtained by using the Bean model.[6,27] Indeed, the real part is characterized by positive values while the imaginary part, not reported here, shows a minimum near T_c. Two peaks appear in $\chi_3'(T)$ when the peak effect is observed. The first one, around T_c, is almost independent of the dc magnetic field, whereas that at lower temperatures decreases when H is increased. At magnetic fields $H > 13$ T, only the signal at higher temperatures can be detected. We used this information to extend the H-T phase diagram, up to 19 T. Figure 2 also shows the onset temperature $T^*(\chi_3')$ of the positive peak near T_c in the real part of the third harmonics. It was found that $T^*(\chi_3')$ corresponds to the peak temperature in the first harmonics of the ac magnetic susceptibility. It is remarkable that $T^*(\chi_3')$ can also be individuated in the high-field/low-temperature region, where the dip was no longer detected in the first harmonic measurements. We verified (see Fig. 4) that $T^*(\chi_3')$ is almost independent of the external parameters (frequency and amplitude of the ac magnetic field, angle α between the sample and the dc magnetic field). We identified the $T^*(\chi_3')$ line in the H-T phase diagram as the transition between a disordered and the Bragg glass phase. In such way, the nonlinear signals due to the two different phases can be clearly distinguished in the third harmonic curves. Namely, for $T > T^*(\chi_3')$ there is the peak associated with the

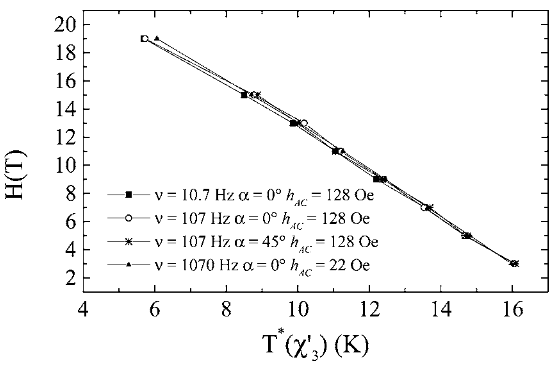

FIG. 4. $T^{*}(\chi_3')$ measured for various amplitudes, h_{ac}, and frequencies, ν, of the ac magnetic field, at the angles $\alpha=0$ and 45° between sample and external field. $T^{*}(\chi_3')$ is almost unaffected by the change of these parameters, thus being a valuable candidate for the transition temperature between the disordered and the Bragg glass phase.

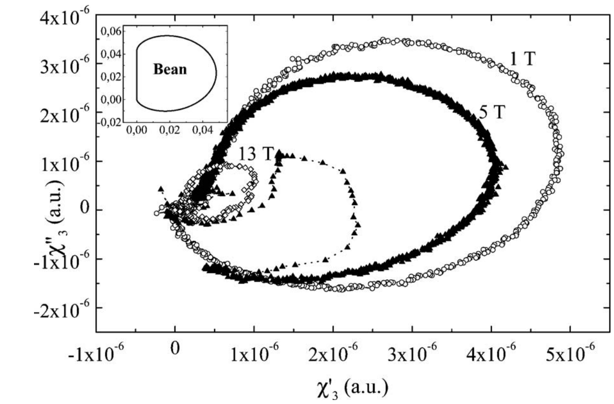

FIG. 5. Cole-Cole plots, defined by the variation of χ_3'', as a function of χ_3', at various dc magnetic fields. Inset: the third harmonic Cole-Cole plots analytically computed by using the Bean model.

disordered phase and for $T<T^{*}(\chi_3')$ the Bragg glass phase signal can be detected. Their shapes and dependences on the external parameters can be very different, depending on the vortex dynamics and the pinning properties, due to the fact that the third harmonics is very sensitive to these variations.[27] Detailed theoretical analysis should be necessary to investigate them. Figure 3 also shows that, at high magnetic fields, the intensity of the third harmonic signal is zero in the temperature range $T<T^{*}(\chi_3')$, i.e., within the Bragg glass phase. The fact that the higher harmonics vanish implies that the magnetic response in the Bragg glass phase is linear at high fields. Further theoretical investigations are necessary to analyze this behavior.

A tendency of the Bragg glass phase toward linearity for increasing dc magnetic fields can be better evidenced by the analysis of the third harmonic Cole-Cole plots, χ_3'' versus χ_3' (see Fig. 5), i.e., the imaginary part of the third harmonics plotted as a function of the real part.[33] At low fields ($H=1$ T), these plots are qualitatively in agreement with those predicted by the static Bean critical state model (inset of Fig. 5):[6,33] a closed loop in the right semiplane. For increasing fields, the peak effect appears in the first harmonics, which is reflected in a decrease of the Cole-Cole plot area and a no-loop structure (see $H=5$ T). The greater contribution is due to the Bragg glass phase, whereas the smaller one is associated with the nonlinear magnetic response of the disordered phase. At higher fields (curve at $H=13$ T), the peak effect is no longer detected and a small loop structure in the third harmonic Cole-Cole plots appears again, only due to the disordered phase, indicating that the Bragg glass phase has an almost linear magnetic response. For $H\geqslant 13$ T (not shown here for major clarity), the plot area is almost field-independent, i.e., the nonlinear magnetic response of the disordered phase is almost constant.

In conclusion, the *H-T* phase diagram and the magnetic response in the Bragg glass phase have been investigated by means of the first and third harmonics of the ac magnetic susceptibility. A peak effect was detected in the compound Nb_3Sn, in a high-quality single crystal. It was confirmed that the third harmonic measurements are a more valuable tool for detailed studies of the *H-T* phase diagram than the first harmonic measurements. In particular, they allowed us to extend the observation of the Bragg glass/disordered phase transition to magnetic fields $H>13$ T, where the first harmonics failed to detect it. The fact that this transition has been observed in Nb_3Sn furnishes a previously missing confirmation of the universality of the phase diagram theoretically predicted by Giamarchi *et al.*[3] in type II superconductors. Finally, our results suggest that third harmonics of χ_{ac} can be used to individuate this transition in all type II superconductors, and possibly also in materials where the peak effect has not been detected so far.

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[1] A. A. Abrikosov, Sov. Phys. JETP **5**, 1174 (1957).
[2] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).
[3] T. Giamarchi and P. Le Doussal, Phys. Rev. B **52**, 1242 (1995).
[4] G. I. Menon, Phys. Rev. B **65**, 104527 (2002).
[5] T. Klein, L. Journard, S. Blanchard, J. Marcus, R. Cibitt, T. Giamarchi, and P. Le Doussal, Nature (London) **413**, 404 (2001).
[6] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962).
[7] W. DeSorbo, Rev. Mod. Phys. **36**, 90 (1964).
[8] G. A. Spiering, E. Revolinski, and D. J. Beerntsen, J. Phys.

Chem. Solids **27**, 535 (1966).
[9] S. Sarkar, S. Ramakrishnan, A. K. Grover, C. V. Tomy, G. Balakrishnan, and D. McK Paul, Pramana, J. Phys. **58**, 979 (2002).
[10] M. Isino, T. Kobayashi, N. Toyota, T. Fukase, and Y. Muto, Phys. Rev. B **38**, 4457 (1988).
[11] P. L. Gammel, U. Yaron, A. P. Ramirez, D. J. Bishop, A. M. Chang, R. Ruel, L. N. Pfeiffer, E. Bucher, G. D'Anna, D. A. Huse, K. Mortensen, M. R. Eskildsen, and P. H. Kes, Phys. Rev. Lett. **80**, 833 (1998).
[12] P. H. Kes and C. C. Tsuei, Phys. Rev. Lett. **47**, 1930 (1981).
[13] E. Zeldov, D. Majer, M. Konczykowski, V. B. Geshkenbein, V. M. Vinokur, and H. Shtrikman, Nature (London) **375**, 373 (1995).
[14] H. Küpfer, Th. Wolf, C. Lessing, A. A. Zhukov, X. Lançon, R. Meier-Hirmer, W. Schauer, and H. Wühl, Phys. Rev. B **58**, 2886 (1998).
[15] D. Stamopoulos and M. Pissas, Phys. Rev. B **65**, 134524 (2002).
[16] K. Hirata, H. Takeya, S. Miyamoto, T. Mochiku, and K. Togano, Chin. J. Phys. (Taipei) **36**, 215 (1998).
[17] M. Pissas, S. Lee, A. Yamamoto, and S. Tajima, Phys. Rev. Lett. **89**, 097002 (2002).
[18] R. Flükiger, *Concise Encyclopedia of Magnetic & Superconducting Material*, edited by J. Evetts (Pergamon Press, Oxford, 1992), p. 1.
[19] N. Toyota, T. Itoh, M. Kataoka, T. Fukase, H. Takei, and Y. Muta, Physica B & C **135B**, 364 (1985).
[20] T. P. Orlando, E. J. McNiff, S. Foner and M. R. Beasley, Phys. Rev. B **19**, 4545 (1979).
[21] S. H. Autler, E. S. Rosenblum, and K. H. Gooen, Phys. Rev. Lett. **9**, 489 (1962).
[22] Y. Paltiel, Y. Myasoedov, E. Zeldov, G. Jung, M. L. Rappaport, D. E. Feldman, M. J. Higgins, and S. Bhattacharya, Phys. Rev. B **66**, 060503(R) (2002).
[23] X. S. Ling and J. I. Budnick, *Magnetic Susceptibility of Superconductors and Other Spin Systems*, edited by R. A. Hein, T. L. Francavilla, and D. H. Liebenberg (Plenum Press, New York, 1991), p. 377.
[24] M. Angst, R. Puzniak, A. Wisniewski, J. Jun, S.M. Kazakov, and J. Karpinski, Phys. Rev. B **67**, 012502 (2003).
[25] H. Küpfer, G. Linker, G. Ravikumar, Th. Wolf, A. Will, A. A. Zhukov, R. Meier-Hirmer, B. Obst, and H. Wühl, Phys. Rev. B **67**, 064507 (2003).
[26] F. Gömöry, Supercond. Sci. Technol. **10**, 523 (1997).
[27] M. Polichetti, M. G. Adesso, and S. Pace, Eur. Phys. J. B **36**, 27 (2003).
[28] M. Marchevsky, M. J. Higgins, and S. Bhattacharya, Nature (London) **409**, 591 (2001).
[29] R. Lortz, N. Musolino, and A. Junod (unpublished).
[30] Y. Paltiel, E. Zeldov, Y. N. Myasoedov, N. Shtrikman, S. Bhattacharya, M. J. Higgins, Z. L. Xiao, E. Y. Andrei, P. L. Gammel, and D. J. Bishop, Nature (London) **403**, 398 (2000).
[31] U. Welp, A. Rydh, G. Karapetrov, W. K. Kwok, G. W. Crabtree, C. Marcenat, L. Paulius, T. Klein, J. Marcus, K.H. P. Kim, C.U. Jung, H. S. Lee, B. Kang, and S.I. Lee, Phys. Rev. B **67**, 012505 (2003).
[32] Y. Paltiel, E. Zeldov, Y. Myasoedov, M. L. Rappaport, G. Jung, S. Bhattacharya, M. J. Higgins, Z. L. Xiao, E. Y. Andrei, P. L. Gammel, and D. J. Bishop, Phys. Rev. Lett. **85**, 3712 (2000).
[33] M. G. Adesso, M. Polichetti, and S. Pace, Physica C **401**, 196 (2004).