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Stability and metastability of disordered vortex phases

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Abstract

Pronounced thermomagnetic history effects, implying metastability of vortex phases, are observed in the low-T_c system 2H-$NbSe_2$. Some special experimental consequences of metastability are summarized. © 2000 Published by Elsevier Science B.V. All rights reserved.

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The low-T_c anisotropic superconductor 2H-$NbSe_2$ is particularly suitable for the study of the competition and interplay among interaction, quenched disorder and thermal fluctuations due to the experimentally convenient parameters [1]. Thermal fluctuations are expected to melt the vortex lattice into two slivers of liquid phase surrounding the solid phase, while quenched disorder is expected to destroy the ordered solid phase and yield glassy phases with residual quasi-long-range or short-range order [2].

We focus on a pronounced peak effect (PE), i.e., the occurrence of a sharp peak in the critical current in this system. The origin of this effect and its relation to possible phase transformations in the vortex state has been a subject of intense work in recent years [1,3–9].

Within the Larkin–Ovchinnikov [10] collective pinning scenario, the critical current J_c for the onset of motion of vortices is given by: $J_c B = (n_p f^2/V_c)^{1/2}$, where n_p is the density of pins, f is the elementary pinning interaction and V_c is the correlation volume. The rapid increase of J_c at the PE is usually attributed to a rapid drop in the correlation volume V_c. In the present system, transport studies [7] revealed the importance of plasticity in

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the PE regime in reducing the effective V_c beyond what is expected for a purely elastic lattice.

The effects of plasticity on the order–disorder transition in the pinned phases were studied in single crystal samples of 2H-$NbSe_2$ with varying pinning. With enhanced pinning, marked history dependence was observed in the magnetic response studies by both ac and dc magnetic techniques [5,6,8]: the field-cooled (FC) state and the zero-field-cooled (ZFC) state produced very different values of J_c, i.e., different values of the correlation volume V_c. Fig. 1 shows the temperature dependence of the ac

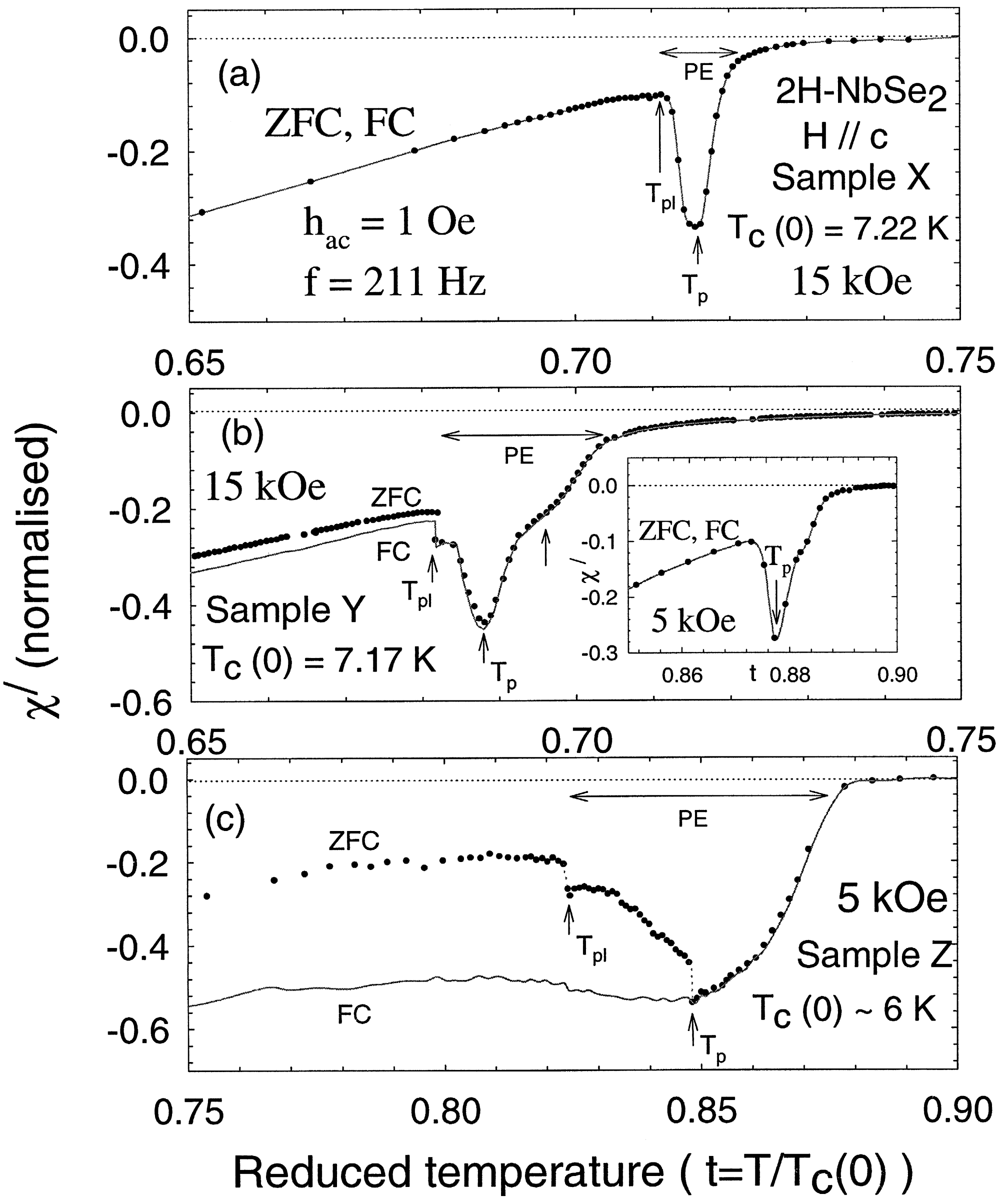

Fig. 1. ac susceptibility in vortex states prepared by FC and ZFC methods in the three samples under study. Panel (c) shows the broadened PE regime with the onset of the PE in the ordered ZFC branch at T_{pl} and the end of the PE regime at T_p, above which the history effect disappears.

susceptibility χ' for three crystals, X, Y and Z, in ascending order of pinning. Within the critical state model, the ac response is given by: $\chi' \sim -1 + (\alpha h_{ac}/J_c)$, where α is a geometrical constant and h_{ac} is the amplitude of the ac field. Thus, a larger value of χ' implies a larger J_c, and, hence, a smaller V_c. In the cleanest sample X, no history dependence was observed. In sample Y, weak history effects were observed at higher H and lower T, but were absent as in the inset, at higher T and lower H. In sample Z, the most strongly pinned system, a very pronounced history dependence was observed, as shown in panel (c) of Fig. 1. The history effects vanish above an apparent discontinuous transition in the χ' ZFC data at the peak at T_p, above which the vortex system is amorphous in equilibrium. Following earlier nomenclature [1,5,6], we attribute the regime below the PE as the conventional LO collective pinning regime of a quasi-lattice. The onset of the PE at the (H_{pl}, T_{pl}) line is assigned to the onset of plasticity and/or a coexistence of ordered and disordered phases and the peak in J_c at the (H_p, T_p) line marks the full amorphization of the lattice [4]. These results show that enhanced pinning broadens the PE regime and destabilizes the quasi-lattice in favor of a plastically deformed state. In addition,

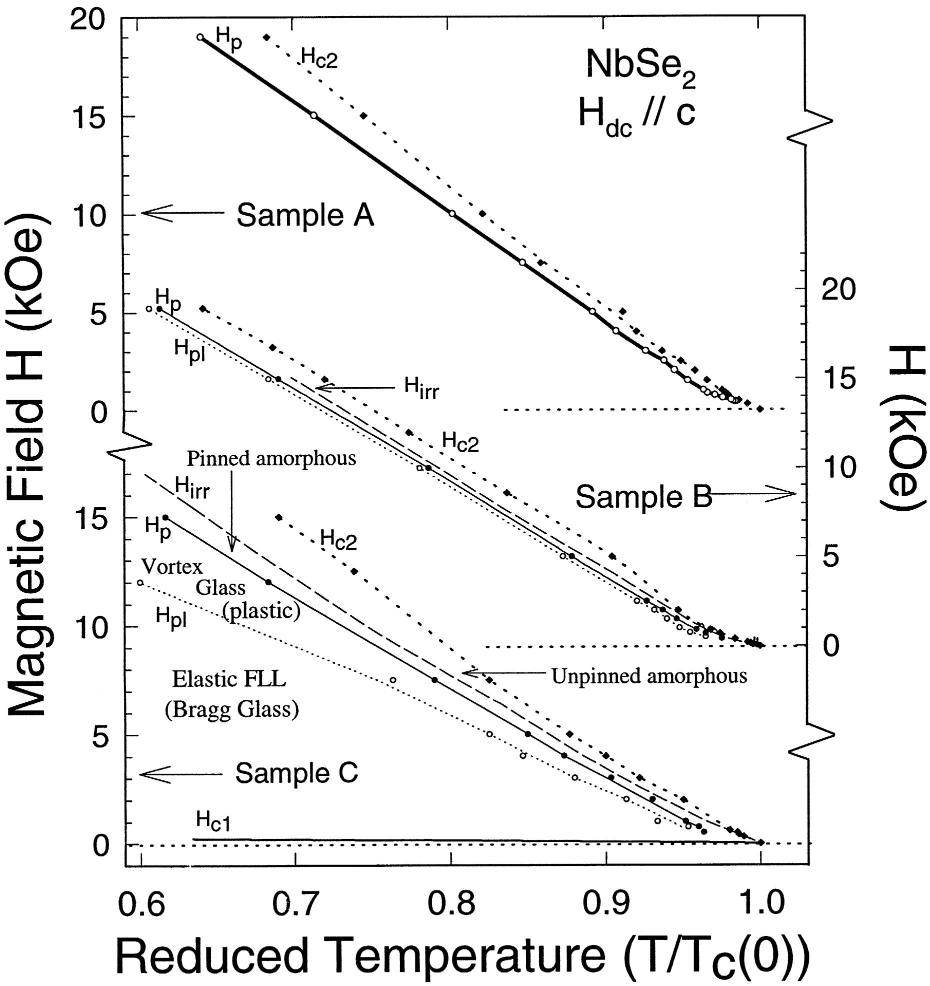

Fig. 2. Vortex phase diagram in samples with varying disorder. The plastically deformed (Vortex glass) state widens with increased pinning at the expense of the ordered (Bragg glass) phase.

strong metastability appears, making the establishment of a truly equilibrium phase behavior ambiguous in some parts of the phase diagram.

The apparent ''phase diagram'' for the ZFC state of each of three crystals is shown in Fig. 2, which demonstrates the shrinkage of the lattice (Bragg glass)

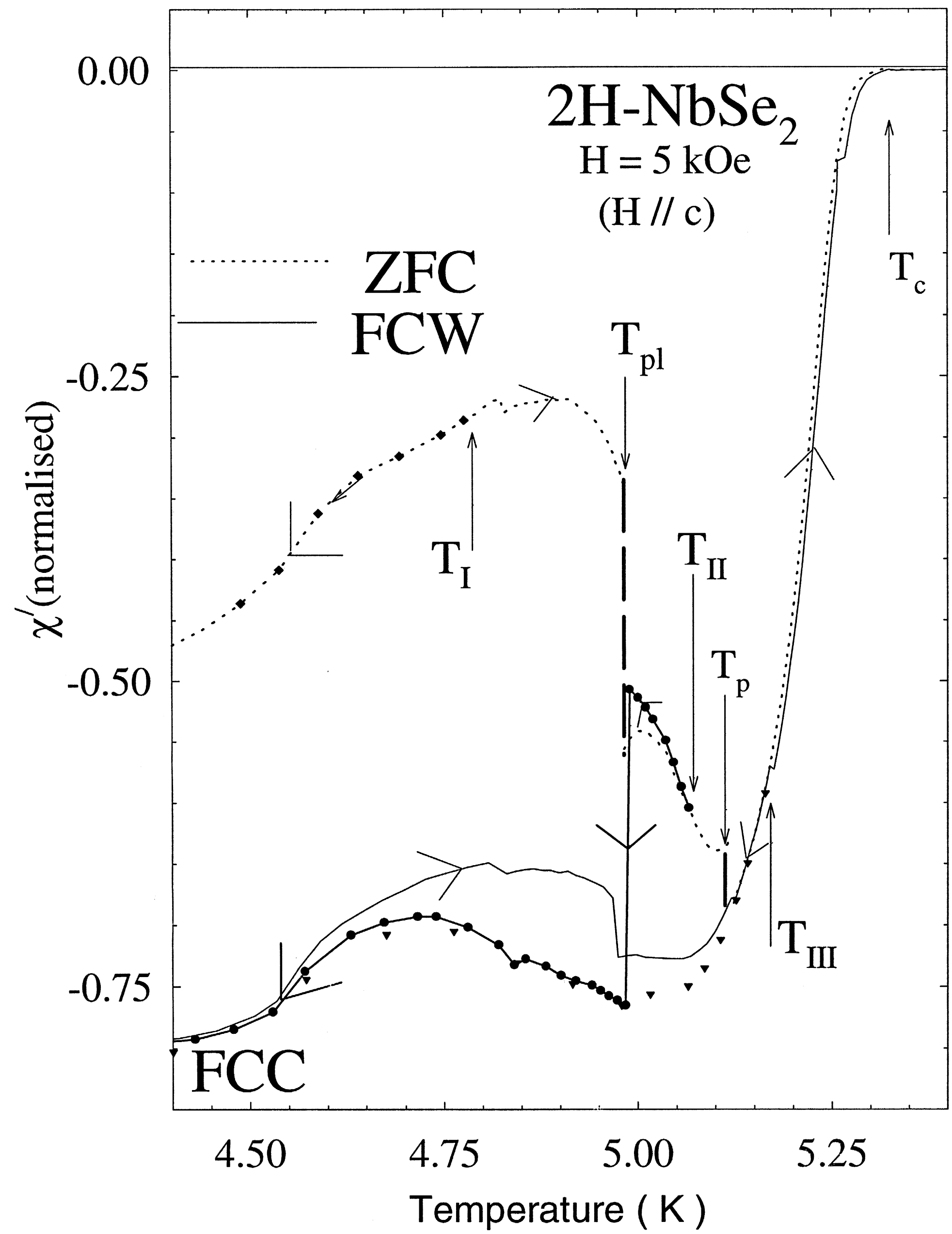

Fig. 3. Anomalous thermal cycling and disorder-induced fracturing of the vortex lattice. The dotted and solid curves denote χ' for ZFC and field-cooled warm-up (FCW). The three sets of data points refer to χ' data recorded while cooling down from $T_I (< T_{pl})$, T_{II} (between T_{pl} and T_p) and T_{III} ($> T_p$), respectively.

phase and the expansion of the plastically deformed (Vortex glass) regime. Further, the onset of reversibility above the so-called irreversibility line also moves away from the peak line, thereby enhancing the regime of stability of the pinned amorphous phase. This stability is presumably the cause for the supercooled FC state that retains the frozen-in amorphous correlations and is, thus, more strongly pinned. The ZFC phase, in contrast, is prepared by exposing the superconducting sample to a magnetic field. The vortices, thus, invade the sample at high velocities and are able to overcome the effects of pinning centers to eventually explore the ordered (meta) stable state. In the FC mode, the vortex lines get nucleated around pinning centers as one enters the superconducting phase. Recent neutron scattering data [11] confirm that the ZFC phase is indeed more ordered than the FC phase.

In what follows, we describe two effects of metastability of the vortex state. First, we describe a highly anomalous temperature cycling result in the most strongly pinned sample Z. Fig. 3 shows that the ZFC branch remains robust under thermal cycling as long as T does not exceed T_{pl}. If the cycling point exceeds T_p, the amorphization point, then upon reducing T, the system follows the FC branch instead, i.e., a disordered phase is ‘‘supercooled’’ from above. However, if the cycling is done from T in between T_{pl} and T_p, then upon a reduction of T, the system crashes nearly down to the FC branch instead of reaching the ZFC state. This yields an apparently open hysteresis loop, i.e., an irreversible effect under thermal cycling. We note that this effect is analogous to a fracturing of clamped solids. This behavior is not observed in the purer crystals showing that it is caused by enhanced pinning. Second, a transformation from the disordered FC state to the ordered ZFC state at $T < T_{pl}$ can also be accomplished by a shaking of the lattice, i.e., by the application of a large ac field. This method provides a ‘‘switch’’ from a high-J_c state to a low-J_c state. The reverse switch can be effected by a heat pulse that temporarily heats up the system above T_{pl}. The details of this critical-current switches are given elsewhere [9].

These results show that when a disorder-induced first-order phase transformation occurs between an ordered and a disordered phase, and when thermal fluctuations are weak, strong metastability is generically present. It is experimentally unclear how one can unambiguously establish the equilibrium nature of the phases and relate to the theoretical phase diagrams. On the other hand, strong metastability can also be utilized for potential applications as in the case for the shaking-induced switching effect.

References

[1] M.J. Higgins, S. Bhattacharya, Physica C 257 (1996) 232, and references therein.

[2] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125, and references therein.

[3] R. Wordenweber, P.H. Kes, Phys. Rev. B 33 (1986) 3172.

[4] P.L. Gammel, U. Yaron, A.P. Ramirez, D.J. Bishop, A.M. Chang, R. Ruel, L.N. Pfeifer, E. Bücher, G.D. Ànna, D.A. Huse, K. Mortensen, M.R. Eskildsen, P.H. Kes, Phys. Rev. Lett. 80 (1998) 833.

[5] S.S. Banerjee, N.G. Patil, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, P.K. Mishra, T.V.C. Rao, V.C. Sahni, M.J. Higgins, C.V. Tomy, G. Balakrishnan, D. Mck. Paul, Phys. Rev. B 59 (1999) 6043.

[6] S.S. Banerjee, N.G. Patil, S. Saha, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, T.V.C. Rao, V.C. Sahni, M.J. Higgins, E. Yanamoto, Y. Haga, M. Hedo, Y. Inada, Y. Onuki, Phys. Rev. B 58 (1998) 995.

[7] S. Bhattacharya, M.J. Higgins, Phys. Rev. Lett. 70 (1993) 2617.

[8] G. Ravikumar, V.C. Sahni, P.K. Mishra, T.V.C. Rao, S.S. Banerjee, A.K. Grover, S. Ramakrishnan, S. Bhattacharya, M.J. Higgins, E. Yanamoto, Y. Haga, M. Hedo, Y. Inada, Y. Onuki, Phys. Rev. B 57 (1998) R11069.

[9] S.S. Banerjee, N.G. Patil, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, P.K. Mishra, T.V.C. Rao, V.C. Sahni, M.J. Higgins, Appl. Phys. Lett. 74 (1999) 126.

[10] A. Larkin, Y. Ovchinnikov, J. Low Temp. Phys. 34 (1979) 409.

[11] D. Mck. Paul et al., to be published.