Multicriticality in the Bragg-Glass Transition

The discovery [1] of a first-order solid-liquid transition in the vortex matter of a classic type-II superconductor niobium was widely regarded as an important result since it resolved a long-standing issue of whether a genuine order-disorder transition can take place in the vortex system in type-II superconductors, and whether the anomalous peak effect is indeed caused by a structural phase transition in the vortex matter. However, in a follow-up SANS experiment [2] on a Nb crystal which has a lower upper critical field, suggesting even less bulk disorder, neither the first-order transition nor the peak effect was found. These two seemingly contradictory results suggest either a trivial technical error in one of the two experiments, or something more profound and interesting in the physics of vortex matter, namely the existence of multicritical behavior in the Bragg-glass transition. We have now carried out a systematic study of the Nb crystal used in our original experiment, and have found such a multicritical point [3].

Our experiment was carried out on a Nb single crystal in which both the peak effect and the first-order Bragg-glass melting transition were observed at the same temperatures [1]. The sample has a zero-field $T_c = 9.16$ K, and an estimated Ginzburg-Landau parameter $\kappa(0) = 2.0$. The experimental SANS configuration is shown in the inset of Fig.1 (a). The dc magnetic field was applied in the direction of the incoming neutron beam using a horizontal superconducting magnet. A coil was wound on the sample to allow *in situ* ac magnetic susceptibility measurements.

Fig.1(a) shows the SANS data at $H = 0.3$ T. The Gaussian widths are obtained from fitting the Bragg peaks (in intensity vs. azimuthal angle) to six Gaussian peaks evenly spaced 60° apart. It is clear that the azimuthal widths — a measure of orientational disorder in the vortex array — are strongly history dependent. Supercooling and superheating effects are observed for field-cooling (FC) and field-cooled-warming (FCW) paths, respectively. As reported previously [1], the disordered phase at $T > T_p$ and the ordered phase at $T < T_p$ are their respective thermodynamic ground states. The abrupt change in the structure factor $S(q)$ at the peak effect T_p depicts a symmetry-breaking phase transition from a vortex liquid with short-range order to a Bragg glass with quasi-long range order [1]. The phase transition is first order as evidenced by the strong thermal hysteresis in $S(q)$. Compared to that at higher fields, the metastability region for $H = 0.3$ T is smaller but still pronounced.

It was found that the thermal hysteresis of $S(q)$ observed in SANS is strongly field dependent, and the metastability region disappears completely at low fields.

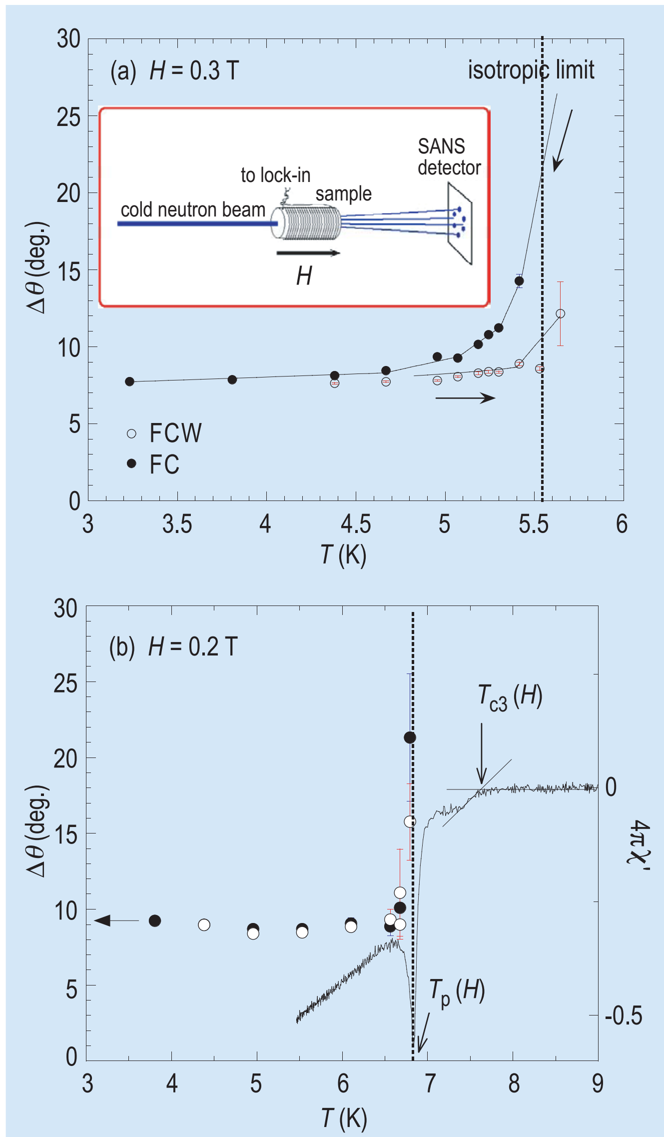

Fig. 1. (a) Temperature and history dependence of azimuthal widths of the (1,-1) diffraction peak at $H = 0.3$ T. The dashed line is the peak effect T_p at this magnetic field based on ac magnetic susceptibility measurements. Inset: experimental configuration. (b) Widths at $H = 0.2$ T. The ac susceptibility data are also shown for reference. Definitions of $T_p(H)$ and $T_{c3}(H)$ are shown.

Fig. 1 (b) shows the azimuthal width data for $H = 0.2$ T. For comparison, the real part $\chi'(T)$ of the ac magnetic susceptibility is also shown in Fig.1(b). The dip in $\chi'(T)$ is the well-established signature of the peak effect [1]. The history dependence of the Bragg-peak width is only detectable within 100 mK of the peak-effect temperature T_p. A similar trend is observable in the history dependence of the radial widths of the Bragg peaks. At 0.3 T, there is a pronounced thermal hysteresis in the radial widths. At 0.2 T, however, the hysteresis is barely discernable. At an even lower field of 0.1 T (data not shown), the thermal hysteresis in $S(q)$ is undetectable.

At $H = 0.1$ T, a very sharp peak effect (the onset-to-end width = 40 mK) is still present. Thus we believe the phase transition at 0.1 T is still first-order but the metastability region is too narrow to be resolved in SANS (the temperature resolution was ≈ 50 mK). Nevertheless, the diminishing hysteresis in the low-field regime suggests that the phase transition is becoming continuous and mean-field-like, namely there is a multicritical point on the phase boundary bordering the Bragg glass on the H-T phase diagram. We show that this multicritical behavior is directly related to the appearance and the disappearance of the peak effect.

Fig. 2 shows a three-dimensional plot of the $\chi'(T)$ as a function of temperature and magnetic field. At high fields, there is a pronounced peak effect, a characteristic dip in $\chi'(T)$. At higher temperatures above the peak-effect temperature $T_p(H)$ (or $H_p(T)$, used interchangeably), there is a smooth step in $\chi'(T)$. This step, $T_{c3}(H)$ (or $H_{c3}(T)$), defined in Fig.1 (b), is the onset of surface superconductivity. In the mean-field theory of Saint-James and de Gennes, $T_{c3}(H)$ is a continuous phase transition. The separation between $T_p(H)$ and $T_{c3}(H)$ grows larger with increasing magnetic field. Upon cooling, below $T_{c3}(H)$ and toward $T_p(H)$, the screening effect in $\chi'(T)$ increases gradually but there is no sharp feature to define another temperature scale. With decreasing field, the peak effect becomes narrower and smaller. For $H < 0.08$ T, there is only a single kink in $\chi'(T)$ corresponding to the mean-field transition $T_{c2}(H)$ or $H_{c2}(T)$. There is no reentrant peak effect at low fields — the peak effect simply vanishes here. New theoretical studies are needed to elucidate the possible physical mechanisms of the multicritical point in a Bragg glass.

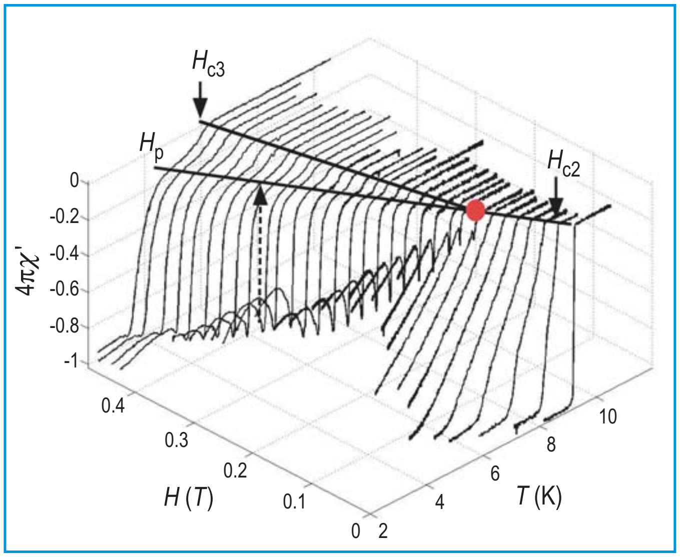

Fig. 2. Three-dimensional (3D) magnetic field and temperature dependence of the real part of the ac susceptibility $4\pi\chi'(T)$. Note that two values of ac fields were used in the measurements. For $H < 0.3$ T, $H_{ac} = 0.17$ mT, and for $H > 0.3$ T, $H_{ac} = 0.7$ mT, $f = 1.0$ kHz. The solid and dashed lines are guides to eyes. For the ac fields used, T_p is independent of the ac field amplitude.

References

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