Experimental report

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Proposal: **5-42-371** **Council:** 4/2014

Title: Dynamic reorganization of vortex lattice in clean NbSe2 single crystals

Research area: Physics

This proposal is a new proposal

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Samples: NbSe2

Instrument	Requested days	Allocated days	From	To
D33	5	4	07/12/2014	11/12/2014

Abstract:

In a recent SANS experiment in NbSe2 crystals, we observed changes in the vortex lattice (VL) structure after different dynamic histories. The main result was the direct evidence that the application of an oscillatory (shaking) field can order or disorder the VL. In this second experiment we propose to study in more detail the changes in the spatial correlation involved in this driven reorganization, and the controversial role of sample boundaries in the observed phenomenology. As vortex matter is considered a model complex system, understanding this dynamic reorganization would have a high impact beyond the vortex community.

Dynamic reorganization of vortex lattice in clean $NbSe_2$ single crystals.

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In a recent experiment in $NbSe_2$ crystals, by combining small angle neutron scattering (SANS) with linear AC susceptibility measurements, we have shown that the application of oscillatory forces in a transitional region near the order-disorder transition results in robust bulk vortex lattice configurations with an intermediate degree of disorder. These dynamically originated configurations correlate with different AC responses, associated with intermediate degrees of pinning. Differences in the AC responses are also observed after thermally cycling the samples in a FC configuration. In this second combined experiment we investigate the possible existence of an associated "spontaneous" thermal reordering. Preliminary results are not conclusive.

In the vortex matter of type II superconductors, competing interactions give rise to a complex dynamics including thermal and dynamic history effects. When cooling a superconducting sample from the normal state under an external magnetic field, energy barriers trap vortex lattices in highly disordered metastable configurations. However, high transport current densities or large AC magnetic fields allow VLs to reach the stable configuration.

In very low-pinning superconductors, such as clean $NbSe_2$ single crystals, most of the vortex field-temperature phase diagram is properly described by an ordered dislocation-free Bragg Glass (BG) phase[1,2], which undergoes an order-disorder transition (ODT) near the normal-superconductor transition[3]. The fingerprint of the ODT is an anomalous rise of the critical current density known as the *peak effect* (PE). A transitional region between the ordered and disordered phases has been reported[4] and investigated by our group[5,6] using a non-invasive linear AC susceptibility technique: larger in-phase AC susceptibility χ' is related to a larger AC penetration depth λ_{AC}. Whereas in the BG phase a shaking field increases λ_{AC}, in the intermediate region λ_{AC} can be increased or even decreased by the application of a shaking AC field. We have recently reported direct evidence of dynamic reorganization driven by external oscillatory forces in this transitional region[7]: different values of χ' at a given temperature and field measured after the reorganization were correlated to bulk vortex lattice configurations (VLCs) with different degrees of order, supporting a connection between λ_{AC} and bulk pinning in agreement with our previously proposed picture[5,6].

An increase in the linear λ_{AC} has been also observed after thermally cycling the sample in cooling-warming field-cooled processes without any additional dynamic perturbation[5]. In the present experiment we explore whether these differences observed in the response between field-cooled cooling (FCC) and field-cooled warming (FCW) procedures are also connected to a change in the order of the vortex lattice.

The experiment was conducted in the instrument D33, using a special sample holder equipped with a set of coils which allowed measuring the AC susceptibility response *in situ*. The sample used was a large clean $NbSe_2$ single crystal (5 × 5 × 0.2 mm^3). The applied magnetic field **H** was parallel to the crystal's **c** axis and was kept fixed at H = 5 kOe throughout the experiment. Rocking the sample around the vertical axis, we observed sixfold degenerate first order Bragg peaks (BP), aligned with the crystallographic axes and centered at the scattering radius $q_0 = 2\pi(2B/\sqrt{3}\Phi_0)^{1/2}$, with Φ_0= 2 10^{-7} G cm^2. Our experimental setup (neutron wave length λ_N = 7 Å, 12.8 m collimation, 30 mm aperture) limited the resolution to $\Delta q_{r,a} \sim 12\ \mu m^{-1}$ in the radial and azimuthal directions and to $\Delta q_L \sim 0.19\ \mu m^{-1}$ ($\Delta\theta \sim 0.087^0$) along the field direction.

We imaged one of the peaks at the Bragg condition (maximum in-plane intensity) after the following thermal and dynamic histories at various temperatures T_m:

- FCC configurations were obtained by cooling the sample in a field cooled procedure from the normal state down to T_m.
- FCW configurations were obtained by warming the sample up to T_m after a FCC procedure down to the lowest temperature (~ 3.2 K).
- "Shaken" (SHK) configurations were obtained after applying 100 cycles of a shaking field (7 Oe, 1 kHz) at T_{sh} ~ 5.5 K and then cooling and/or warming the sample to T_m.

Due to the beam-time constraint we were able to acquire the full rocking curves (RCs) after the histories described only at two temperatures T_m = 3.2 K and T_m = 4.6 K.

RCs of the FCC and shaken VLs acquired at the lowest T_m = 3.2 K are compared in Figure 1a. As reported in Ref.7, the rise of ξ_L beyond our resolution together with an increase in the intensity I_{max} at the Bragg condition $\theta = \theta_0$ after shaking indicates an ordering of the VL. No significant changes are observed in the integrated intensity. In Figure 1b, the RCs of the same configurations at T_m= 4.6 K are shown and compared with the corresponding FCW. Although the FCW RC shows a subtle increase in I_{max} with respect to the FCC RC, the associated difference in the angular width $\Delta\theta$ (and therefore in ξ_L) is in the limit of the experimental uncertainty.

Figure 2 shows the linear AC susceptibility $\chi'(T)$ measured *in situ* during FCC and FCW procedures, and after shaking the VL. As reported in previous works[5], λ_{AC} is strongly reduced and the PE is not observed during the FCC procedure. While warming the sample in the FCW procedure, λ_{AC} increases, suggesting a decrement of the effective pinning. The pinning is further decreased after shaking the VL.

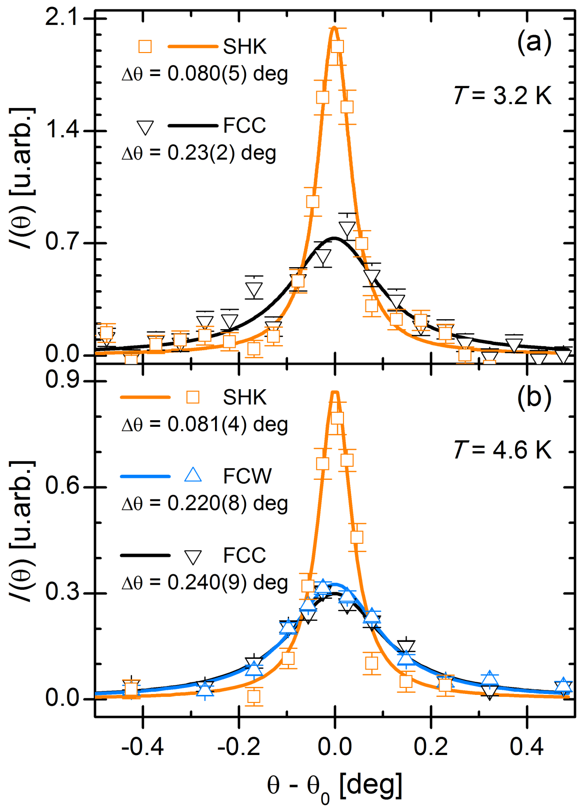

Figure 1: Rocking curves measured at T_m = 3.2 K (a) and 4.6 K (b) after various histories. Measured data (symbols) and their corresponding fitted Lorentzian curves (lines) are shown. Fitted values of Δθ (FWHM) are indicated in the legend. The background has been subtracted..

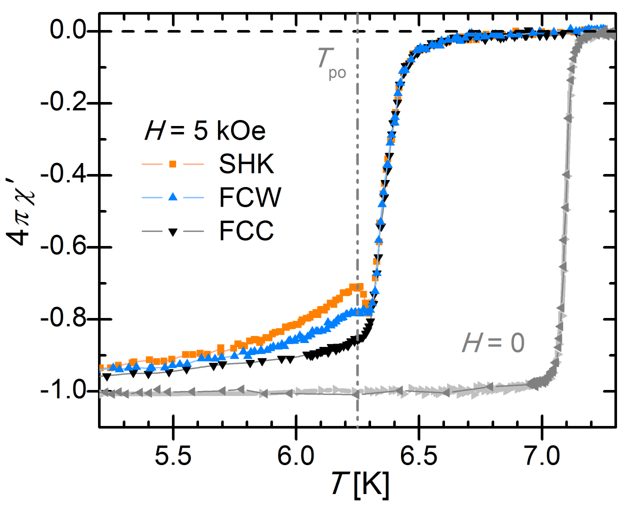

Figure 2: Normalized linear AC susceptibility measured *in situ* using a small AC driving field (10 mOe, 65 kHz). Matching zero-field transitions measured while warming (light gray) and cooling (dark gray) indicate good thermal contact between the sample and the thermometer. Symbols corresponding to various histories at H = 5kOe are indicated in the legend.

The evolution of I_{max} as a function of temperature during FCC and FCW procedures is shown in Figure 3. The intensity of the shaken VL is also plotted for comparison. I_{max}(FCW) is in fact slightly larger than I_{max}(FCC), in agreement with a spontaneous ordering of the VL. However, the variations between different realizations are on the same order that the observed increase; therefore, this result is not conclusive. Moreover, as reported in Ref.7, I_{max}(SHK) is clearly higher than both I_{max}(FCC) and I_{max}(FCW) for all measured temperatures.

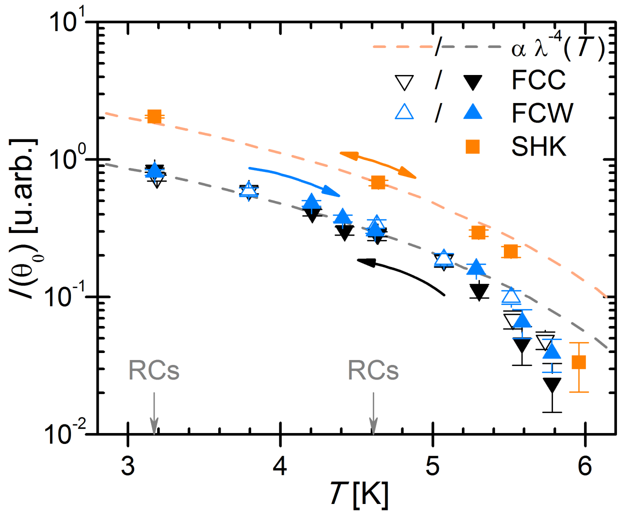

Figure 3: Maximum scattered intensity I_{max}, measured at the Bragg condition, after background subtraction. Symbols corresponding to various histories at H = 5 kOe are indicated in the legend; full and open symbols correspond to different realizations of the FCC/FCW procedure. Dashed lines are proportional to $\lambda_L^{-4}(T)$ extracted from Ref.8, with the factor chosen to match our low-temperature data.

The temperature dependence of I_{max} displays another striking feature: whereas for a fixed VL configuration $I_{max}(T)$ is expected to behave as $1/\lambda_L^4(T)^2$, where λ_L is the London penetration depth, a steeper drop of I_{max} is observed above T ~ 5.2 K in all the configurations.

In summary, our data is compatible with a spontaneous ordering of the VL while cooling the sample in a FC process, but these results are not conclusive. Moreover, such an ordering seems to be marginal in comparison with the effect of shaking the VL, at least at temperatures below the maximum T_m in our experiment. Therefore, the considerable difference between linear susceptibility signals in FCC and FCW processes is probably originated by something else than the bulk degree of order. The cause of the fall in I_{max} beyond what is expected due to the smearing of the structure factor remains also an intriguing puzzle. Better statistics and higher-temperature RCs are required in order to solve these questions.

Work fully performed at ILL.
Proposal number: 5-42-371; Instruments: D33.

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