Observation of the Correlated Vortex Flow in $NbSe_2$ with Magnetic Decoration.

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In weakly pinning type-II superconductors the vortex lattice can flow coherently under the action of a Lorentz force. This type of collective vortex motion in a random potential is manifested by channeling of the vortex flow along preferred paths which are stable in time. We present direct experimental observations of such vortex flow "channels" obtained with magnetic decoration experiments on $NbSe_2$ single crystals. [S0031-9007(96)02197-7]

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Recently, both theoretical and experimental interest has been turning to the behavior of the vortex lattice (VL) in type-II superconductors moving under the action of Lorentz forces from an applied current. Especially, several studies were made of the depinning process and the onset of the lattice motion [1–4]. A novel contribution to the subject was made by the authors of Ref. [5]. They showed that if pinning in the superconductor is weak and the driving force is strong enough an initially defective vortex configuration recrystallizes into a coherently moving perfect vortex lattice above certain critical flow velocity v^*. The lattice is oriented with one of its principal directions along the direction of motion, as was earlier suggested by the experiments of Fiory [6]. Recently, however, a somewhat new approach to the problem was proposed in Ref. [7]. One major new conclusion from that work is that static disorder remains in the moving system, which suggests the formation of a moving vortex glass rather than perfect lattice in $d > 2$. Most interesting from an experimental point of view was a prediction of the existence of static, elastically coupled "channels" for vortex flow in a weakly disordered system, in contrast to motion along random paths. These channels form for any velocity $v > 0$ of the vortex configuration. A direct experimental observation of the flux-flow pattern at the level of the individual vortices could provide a proof for this new theory.

In this Letter we report direct high-resolution imaging of vortex-flow patterns using magnetic decoration. The decoration technique is a well-known method to visualize flux distributions at the surface of the superconducting sample, and it has been extensively used for the imaging of static vortex patterns in both conventional and high-T_c superconductors. A decoration pattern normally results from a snapshot of the magnetic field distribution at the sample surface averaged over the duration time of the decoration t_d. This time t_d is given by the experimental conditions and normally is of the order of 0.1–1 s. It is, therefore, clear that in only some specific cases motion can be probed with the decoration technique. For instance, one can try to decorate the flowing flux pattern. That is possible only if the pattern remains essentially stable within the decoration time t_d. If vortices move along one line, time averaging of the attraction of the particles over the deposition time leads to a decorated track of the vortex flow channel. However, turbulence or just wiggling with an amplitude comparable to the distance to a next channel is destructive for obtaining images of that type and will result in an approximately random distribution of the magnetic particles at the sample surface. Several examples of "decoration in motion" have been reported previously [8–10], but trajectories of the individual vortices have not been resolved in those experiments. Here we make an extension to the described method, improving its resolution to the intervortex spacing, and observe a novel type of ordered vortex motion.

One can also imagine that if the moving vortex configuration is stopped it may still preserve the essential features of the previous, moving configuration. It can be argued that at temperatures far below T_c the stiffness of the VL, given by its shear modulus c_{66} and tilt modulus c_{44}, is already sufficiently large to prevent long-wavelength relaxations, reorientations of the large vortex grains, etc. after the driving current has been switched off. This problem has been recently studied with small angle neutron scattering (SANS) [11] and decoration [12] experiments performed on $NbSe_2$. It was seen that the well-ordered state of the moving VL was preserved after the VL was suddenly stopped.

In the following we apply the decoration method to study the dynamics of the vortex configuration formed by the flux penetration in a zero-field cooled (ZFC) superconducting platelet. Our experiments were carried out on single crystals of $NbSe_2$, which is a layered superconductor with $T_c = 7.1$ K. Pinning is weak in this material; transport measurements of the critical current density give $J_c \simeq 5 \times 10^3$ A/cm^2 in an applied field of 50 Oe at 4.2 K. The ratio J_c/J_0 is then $\sim 10^{-4}$, where J_0 is the depairing current density at the same temperature. Crystals were platelets with typical transverse sizes ~1 mm and thickness ~ 50 μm. It is known that in weak pinning materials in platelet geometry vortex penetration is governed by the edge barrier effect [13,14]. When an external magnetic field is applied to such a sample, penetration of the magnetic flux into the sample interior begins at the penetration field $H_p = H_{c1} \times \sqrt{d/W}$; here H_{c1} is the lower critical field, W the sample half-width, and d its thickness [14]. In the absence of pinning vortices accumulate in the sample center. However, in real samples, edge defects and shape irregularities locally lower H_p which significantly changes the penetration picture. Vortices first enter at weak spots on the sample edge and form a flux droplet which grows towards the center of the sample when the external field is increased. Droplet growth is stopped by the pinning. Droplets are characterized by a specific shape and a high degree of order in the VL close to the droplet front, as we showed in a previously reported decoration study on platelets of $NbSe_2$ [15]. Therefore droplets are relatively well-defined objects for studying motion-related phenomena. Although not on the scale of single vortices, this can also be demonstrated with a magneto-optical technique. Figure 1(a) shows flux penetrating into a $NbSe_2$ platelet, visualized by measuring the Faraday rotation of polarized light, transmitted through a garnet indicator film. The temperature was 4.5 K, and a magnetic field was applied to ZFC samples with a linear sweep from zero to 65 Oe. Within the experimental resolution of the method (several microns) a gradual growth (without "jumps") of the flux droplets with external field was observed. For the sample in Fig. 1(a) one can estimate that the sweep rate of 1 Oe/s leads to a velocity of the penetrating front v_p of about 50 μm/s. It is important that such experiments can be done without application of the external current to the sample, and, therefore, problems with sample heating due to dissipation in the current contacts can be avoided.

Decoration experiments were done as follows. First samples were cooled to 1.5 K in a very low applied external field of about 1 Oe. Then at that low temperature the applied field was linearly increased up to about 80 Oe with a rate of 1 Oe/s. At a value of approximately 50 Oe the decoration filament was heated up for about 1 s. In our setup a piece of Ni wire is evaporated and it has to be heated above its melting temperature with a tungsten filament. The behavior of the filament resistance during decoration suggests that it takes ~200 – 300 ms to melt the wire, and, therefore, ferromagnetic material is only evaporated during the rest of the decoration time. Earlier experiments [9] suggested that the time window of particles deposition is nearly the same as the evaporation time.

The low-magnification image in Fig. 1(b) shows a decoration pattern of a penetrated flux "cloud" in one of the samples studied. The edge of the sample is below the bottom of the image. The shape of the flux patterns was found to be much more complicated and irregular

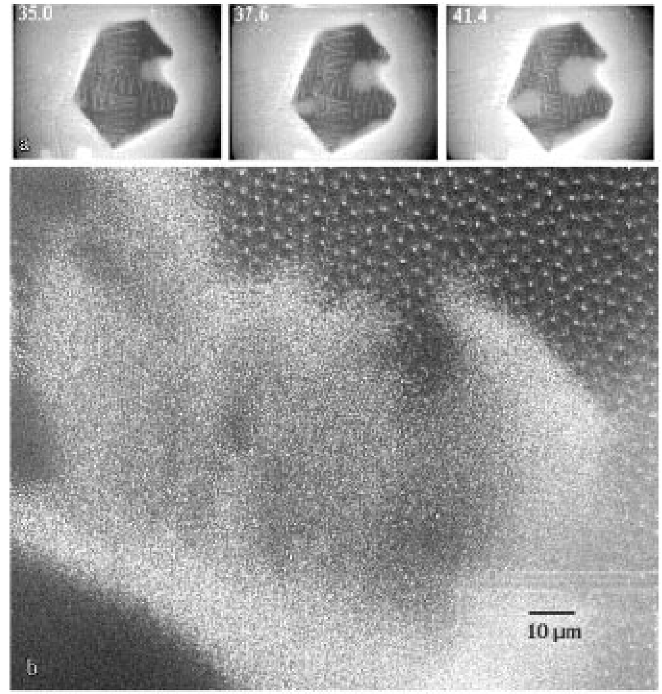

FIG. 1. (a) Magneto-optical images taken on $NbSe_2$ single crystal at $T \sim 4.5$ K during an increase of the external field from zero to 65 Oe. Sample size is about 1 mm. The external field is indicated in the images (in Oe), the gray scale shows a range of approximately 55 Oe, white corresponding to the highest field. Two flux droplets penetrate from opposite edges of the crystal at $H_a \approx 32$ Oe. They grow gradually with increase of the field. (b) Result of decoration with a field sweep 1 Oe/s (different sample). The filament was switched on for about 1 s when external field reached 50 Oe. The image shows a penetrating cloud of magnetic flux.

than in either the magneto-optical or in our previous static decoration experiments. In the latter case, under similar conditions, mostly oval-shaped droplets of the penetrated flux were seen. One reason for the inhomogenieties in the flow could be that heating of the sample caused by the decoration procedure induces viscosity changes in the moving vortex "fluid." In our experiments the temperature goes up to 3.0 K during decoration. As to the vortex structure inside the cloud, one can see that the pattern is substantially smeared, presumably due to the motion of the vortices during the decoration time. Except for a few small regions, no sharp regular dot pattern is seen inside the cloud. It is thus evident that most of the vortices moved. Some regions, however, are less smeared than others, again indicating a rather inhomogeneous distribution of vortex velocities in the penetrating droplet. In contrast, the field-cooled vortices of the 1 G remanent field, which are observed beyond the penetrated front, remained immobile and are well resolved. Another image, taken at the front of the penetrated region, is shown in Fig. 2(a). One can clearly see two line patterns (denoted by arrows) intersecting in the middle of the image under an angle of ~30°. Neighboring lines are nearly parallel, with a well-defined distance between them of about 0.9 μm. If that is taken as a vortex lattice parameter, we obtain an induction of 29.5 G, which is a typical value for the field inside the droplets observed earlier with our decoration experiments [15]. It is suggestive to think, therefore, that the trajectories of individual vortices have been resolved. In view of the previous discussion one can claim that the vortex flow was laminar in those regions; vortices were moving along well-defined, essentially straight channels. We observed similar line patterns in several other samples. Above the two "coherent" regions at the very top of the image in Fig. 2(a), neither static nor moving vortices have been resolved. Presumably, that is due to the turbulence created by the intersection of the two flowing lattices.

Another interesting observation was made close to the sample edge, far away from the large cloud [Fig. 2(b)]. Here vortices just started to penetrate the sample, and one can see a peculiar fingering of the flux front. Every "finger" represents a trajectory along which the vortices move one by one to the sample interior. They are well separated and regular; the distance between neighboring fingers roughly corresponds to an induction of 25–30 G. A similar type of the moving vortex trajectories at the penetrating front in weak-pinning materials has been recently found with numerical simulations [16]. It is especially interesting that these regular channels start directly out of the vortex "belt" close to the sample edge, which is known to be a region of high topological disorder and of strong vortex density gradients [15]. This phenomenon can be also interpreted as a formation of the elastic channels proposed in Ref. [7].

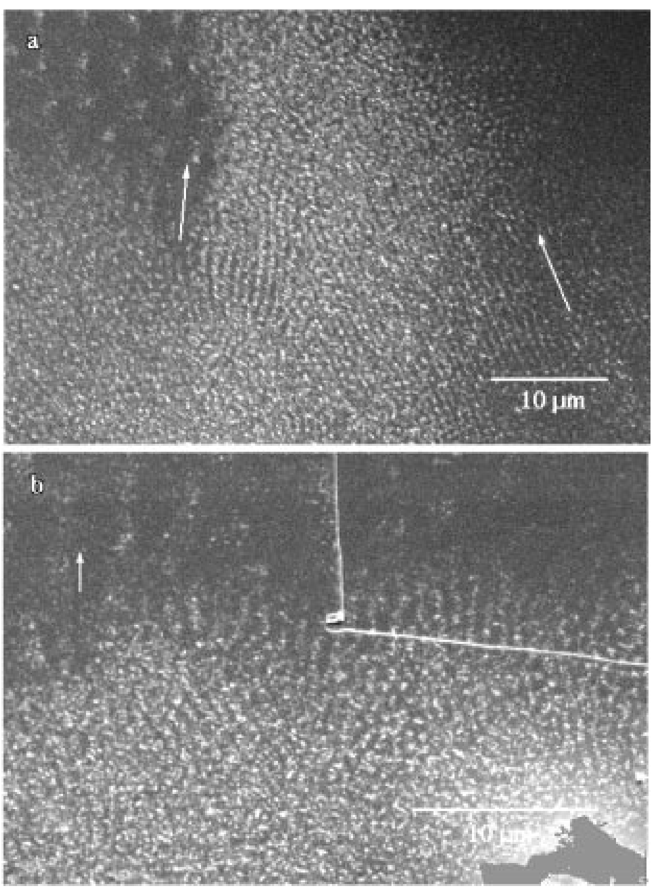

FIG. 2. (a) Two line patterns (denoted by arrows) are seen close to the penetrating front. Channels of vortex flow (linear traces) intersect in the middle of the image under an angle of $\sim$30°. Neighboring channels are nearly parallel, with a well-defined distance between them of about 0.9 μm. (b) Image taken close to the sample edge (which is slightly below the bottom of the image). The very beginning of penetration manifests itself in finger-like channels starting out of the vortex belt along the sample edge.

Regions with channel patterns, as in Fig. 2, were observed in all the samples decorated in this way. In Fig. 3 we use one of these to make some estimates of the correlations in the channel flow pattern. This decoration image was obtained close to the front of a penetrated flux region. The size of the region of the correlated flow was rather large in this case ($\sim$30 μm in diameter). We used part of the pattern outlined with a box to produce the 2D autocorrelation function of the pattern. The original gray-scale image was used in this calculation. The autocorrelation function is defined as

$$G(\delta x, \delta y) = \int I(x + \delta x, y + \delta y)\, I(x, y)\, dx\, dy\,,$$

where $I(x, y)$ is the image brightness. $G(\delta x, \delta y)$ gives the probability to find a similar degree of brightness if one moves a distance $\boldsymbol{\delta} = (\delta x, \delta y)$ from a specific point. The same type of analysis was first performed in Ref. [17] for static decoration images on YBCO. Our result is shown in the inset of Fig. 3. One sees a line pattern superimposed on the hexagonal structure. The decay of the intensity of

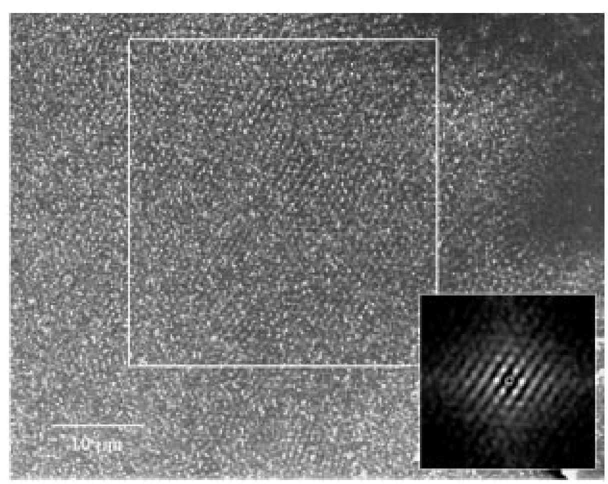

FIG. 3. Decoration image of part of a penetrating flux front. A line pattern of vortex flow in the direction perpendicular to the front is seen. Inset: the 2D autocorrelation function of the central part (outlined) of the decoration image. A flow line pattern with a hexagonal trend superimposed is seen.

the line pattern reveals a correlation length of the flowing VL in the direction perpendicular to the flow direction of about 8–10 lattice parameters. The correlation length along the direction of the channels yields a similar number. We think, however, that the latter is significantly affected by the field gradient in the flow direction. The presence of the hexagonal pattern related to a static lattice suggests that at least during some portion of the decoration time (parts of) the lattice remained immobile. Interestingly, a slight ($\sim$7.5%) "compression" of the static lattice in the direction of the surrounding vortex flow is seen. This might be related to compressional effects of the flow upon the static lattice parts and needs a separate investigation. In Fig. 4 a reconstruction of the channel pattern made by Fourier filtering the original image is shown. The figure shows that there are several regions of disordered flow embedded in the line pattern. Their origin could be a gradient of the induction in the sample, which is seen as a changing in density of the flow lines from the left bottom to right top corner of the image. Also, one can see three single-row dislocations in the flow pattern (marked with squares). Surprisingly, the flow lines around them are not much distorted suggesting that the dislocations did not move significantly during the decoration time. Similar static defect structures have been found recently in numerical simulations of moving vortex lattices [3].

Finally, we want to suggest some parallels between the results of the decorations in motion and our earlier results on droplet formation [15]. First, a relation is seen between the well-ordered vortex lattice close to the droplet front and the observed correlated vortex motion. The regular oval shape of the droplets in our static decorations suggests laminar vortex flow at least close to the droplet front. When the external field reaches its final value the vortex lattice channels freeze resulting in the highly ordered VL grains. The orientation of the static VL remains unchanged from the direction of the flow channels, e.g., preferentially normal to the droplet front. Furthermore, an equivalence is suggested between static dislocations in the flow pattern and similar defects in the decoration patterns of the droplets (See, for example, Fig. 3 of [15]).

In conclusion, we performed decoration experiments on moving vortex lattices. We visualized regions of coherent vortex flow in the sample and observed periodic structures of single-vortex flow channels. Channels are nearly parallel and well separated. We also observed static defects in the flowing lattice and estimated correlations in the flow pattern.

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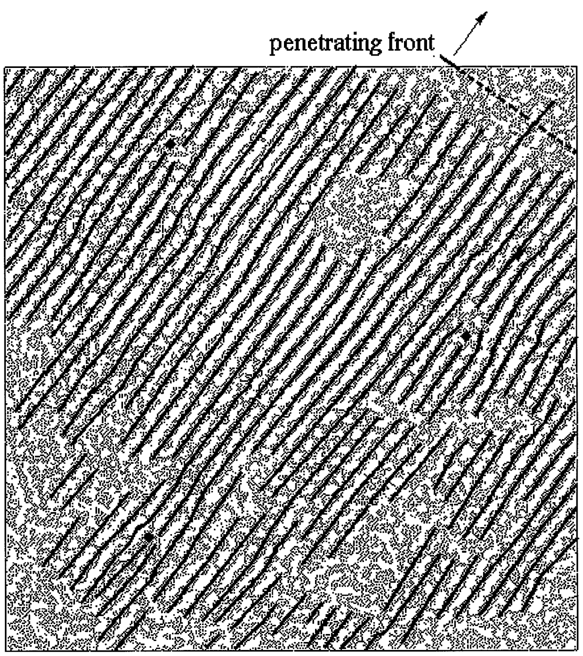

FIG. 4. "Reconstruction" of the channels made by Fourier filtering the original image. Parallel flow lines and regions of disordered flow are seen. Extra rows in the flow pattern ending by dislocations are denoted by solid squares.

[1] S. Bhattacharya and M.J. Higgins, Phys. Rev. Lett. **70**, 2617 (1993).
[2] K. Harada *et al.,* Nature (London) **360**, 51 (1992); A. Tonomura, Jpn. J. Appl. Phys. **36**, 2951 (1995).
[3] D.W. Braun *et al.,* Phys. Rev. Lett. **76**, 831 (1996).
[4] R. Wördenweber, P.H. Kes, and C.C. Tsuei, Phys. Rev. B **33**, 3172 (1986).
[5] A.E. Koshelev and V.M. Vinokur, Phys. Rev. Lett. **76**, 3408 (1996).
[6] A.T. Fiory, Phys. Rev. Lett. **27**, 501 (1971).
[7] T. Giamarchi and P. Le Doussal, Phys. Rev. Lett. **76**, 3408 (1996).
[8] H. Träuble and U. Essmann, Phys. Status Solidi **25**, 395 (1968).
[9] N.V. Sarma and A. Wilcockson, Philos. Mag. **20**, 539 (1969).
[10] L.Ya. Vinnikov, A.O. Golubok, V.A. Marchenko, and G.I. Salnikov, Metallofizika **5**, 103 (1983) (in Russian).
[11] U. Yaron *et al.,* Phys. Rev. Lett. **73**, 2748 (1994).
[12] A. Duarte *et al.,* Phys. Rev. B **53**, 11 336 (1996).
[13] M.V. Indenbom *et al.,* in *Critical Currents in Superconductors,* edited by H.W. Weber (World Scientific, Singapore, 1994).
[14] E. Zeldov *et al.,* Phys. Rev. Lett. **73**, 1428 (1994).
[15] M. Marchevsky, L.A. Gurevich, P.H. Kes, and J. Aarts, Phys. Rev. Lett. **75**, 2400 (1995).
[16] C. Reichhardt *et al.,* Phys. Rev. B **53**, R8898 (1996).
[17] P.L. Gammel *et al.,* Phys. Rev. Lett. **59**, 2592 (1987).