Measurement of Vortex Motion in a Type-II Superconductor: A Novel Use of the Neutron Spin-Echo Technique

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We have used the neutron spin-echo technique to measure the small energy change of neutrons which are diffracted by a moving vortex lattice in a low-pinning Nb-Ta superconducting sample. A transport current was passed in the mixed state to cause flux line movement. In the case of uniform motion, the flux velocity $\mathbf{v}_L$ was given as expected by the values of electric and magnetic fields, via $\mathbf{E} = -\mathbf{v}_L \wedge \mathbf{B}$. We show that with a nonuniformly moving vortex lattice, one can measure the *dispersion* of the velocities, opening up new possibilities for investigating moving vortex lines.

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Despite intense activity in the last few years, only a few experimental methods allow us to measure directly the dynamical properties of moving flux line lattices (FLL's) in superconductors. Recording of I-V curves is of course a most important one, but it provides only global information. On the other hand, neutron diffraction provides a very important contribution by measuring flux line arrangements but is normally used only in static situations. The same is true for muon spin rotation, decoration techniques, etc. In the case of neutrons, a diffraction experiment to demonstrate the motion of flux lines was published many years ago, showing an apparent effect of the relative motion of the FLL and the neutrons [1]. However, the order of magnitude of the observed effect—a change in the Bragg angle—is a factor of 30 smaller than the width of the Bragg peak, which also varies strongly with the current. Hence this experiment is not completely persuasive. Another possibility exists: direct measurements of neutron energy change on diffraction by a moving FLL, which corresponds to reflection by a moving "mirror," leading to a Doppler effect. However, this experiment is quite difficult to perform, due to the weak intensity diffracted at very small angles (typically 0.5° at a neutron wavelength of 15 Å) and to the very small velocity of the FLL (typically <1 ms^{-1}) compared to the neutron speed (about 300 ms^{-1}). The new neutron spin-echo spectrometer IN15 [2] at the Institut Laue Langevin provides a high flux at long wavelengths and an energy resolution down to <10 neV (corresponding to a Fourier time of 10^{-7} s). This is enough to measure the motion of flux lines, not just their average speed, which may be determined with a voltmeter, but also allows the *spread* of velocity values to be determined and observations to be made as a function of diffraction vector $\mathbf{q}$.

Our sample was a $Nb_{87}Ta_{13}$ alloy, rolled into a foil, and spark cut to make a current-carrying bar of 5×0.25 mm^2 cross section and length 30 mm. After cutting, it was annealed at 1500 °C for two days to decrease the critical current [3]. The composition was chosen because it provides both a very low critical current and a high normal state resistivity, in order to obtain a vortex velocity as large as possible for a given current. Using a cryomagnet, a uniform horizontal field of 0.2 or 0.3 T was applied perpendicular to the 5×30 mm^2 face of the sample, which was cooled to 2.2 K, and surrounded by liquid helium to provide efficient cooling. Currents were applied along the bar in the vertical direction; hence the flux lines experienced a force in a horizontal direction in the plane of the sample. The neutron beam was incident nearly parallel to the field. With a single orientation of a hexagonal FLL, this would give a set of six first-order Bragg peaks. Each of these could be maximized in intensity by rocking the cryomagnet so that the angle between the neutron beam and the relevant FLL planes was on the Bragg condition. Even in the absence of an applied current, we observed that the FLL was always aligned so that two of the Bragg spots were in the vertical direction, with the other four at 30° to the horizontal plane. This was probably due to texture induced by rolling during sample preparation [4]. Moreover, this is also the FLL alignment expected to be induced by current flow [5,6], and no reorientation was induced by flux motion.

The neutron wavelength was chosen to be 15 or 19 Å; values in this region satisfied a compromise between the need for angular resolution, energy resolution, and flux intensity. The dispersion of the wavelengths was about 15%. Since there is a magnetic field at the sample, the spectrometer was configured in the "ferromagnetic" configuration [7]. The principle of operation is as follows: an

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incoming neutron is polarized so that its spin precesses (by up to about 10^5 turns) as the neutron passes along the axis of a solenoid coil around the neutron path before the sample. Just before the sample, the neutron spin is then flipped by $\pi/2$, so that the information from the precession in the solenoid is not lost by precession in the large fields in the sample region. The neutron is then scattered by the sample and may change its energy in the process. Just after the sample, the spin of the scattered neutron is again flipped by $\pi/2$ and precesses while the neutron passes along the axis of a second coil. Finally, the polarization of the outgoing neutron is detected by a further $\pi/2$ flipper and spin-analyzing supermirrors in front of a 32×32 cm^2 multidetector. We first consider the case where a neutron undergoes no energy change at the sample, and the line integral of magnetic field along the axis of the second precession coil is the same as for the first. In this case, for a set of incoming neutrons having a range of speeds, the spins are dephased in the first precession coil because neutrons with different speeds undergo different precessions. However, the neutron spin precession in the second coil "undoes" that in the first, for a wide range of neutron speeds, and the maximum polarization is obtained at the analyzer. This is the "spin echo": near this condition, the polarization—and hence the intensity after the analyzer—oscillates as a function of the difference between the currents in the two coils, with a period given by one complete precession. By measuring the neutron counts at four points covering one period of this oscillation, two parameters of the spin echo, the amplitude and the phase, may be determined.

If now we suppose that the scattered neutrons all undergo the same small energy change ε at the sample, they will travel at a different speed through the second precession coil, and a different current in it will be required to restore the original polarization. Hence the phase of the spin echo is a direct measure of this energy change. The change in phase ϕ may be expressed in terms of a quantity t known as the Fourier time of the setup [7], which is proportional to the line integral of the magnetic field along a precession coil (t is thus an experimental parameter controlled by the current in the precession coil):

$$\phi = \frac{\varepsilon}{\hbar}\, t \,. \tag{1}$$

Hence an energy change of the neutrons at the sample will be revealed as a phase change of the spin echo which varies linearly with the precession field in the coils.

If the neutrons acquire a range of energy changes in the sample, the "refocusing" of the spin directions during the second precession is imperfect, and the amplitude of the spin echo is reduced. We may detect this by measuring the change of echo amplitude with precession field/Fourier time. We allow for any changes in the amplitude of the echo due to minor imperfections in the apparatus by measuring the variation of the spin echo amplitude for the neutrons diffracted with no energy change by a static flux lattice.

The energy change of neutrons after diffraction by a moving FLL may be expressed as follows:

$$\varepsilon = \hbar \mathbf{q} \cdot \mathbf{v}_L \,, \tag{2}$$

where $\mathbf{v}_L$ is the vortex velocity and $\mathbf{q}$ is the diffraction vector (of magnitude $q = 2\pi/d$, where d is the Bragg plane spacing of the FLL).

Hence,

$$\phi = \mathbf{q} \cdot \mathbf{v}_L t \,. \tag{3}$$

In the present experiment, the angle between $\mathbf{q}$ and $\mathbf{v}_L$ is 30°. Figure 1a presents a typical result for the amplitude S of the echo and its phase ϕ versus the Fourier time t. The total counting time for each point was typically 5 min. The accuracy of phase determination was enhanced, and long term drifts in echo phase were removed, by taking measurements with both directions of transport current, which gave opposite phase changes [8]. It will be noted that there is nonlinearity in the phase variation and a fall in echo amplitude at large Fourier times. This is due to the presence of a background signal of elastic scattering by the cryostat and the sample holder, which gives an echo out of phase with that due to the moving FLL. The results may be corrected for this background if its magnitude is known. This was determined in two different ways which gave the same result: either the sample was heated into the normal state (10 K) or the sample angle was rocked about a vertical axis away from the Bragg condition. Typical results are shown in the inset in Fig. 1a. The magnitude of the background was normally determined from a rocking curve, since this did not require a temperature change. The results after correction for background are shown in Fig. 1b. We now see that the echo amplitude remains constant and that the phase is proportional to the Fourier time, in agreement with (3). A background correction is applied in all subsequent figures.

In a moving vortex lattice, the average electric field $\mathbf{E}$ is given by the vector product of the vortex lattice velocity $\mathbf{v}_L$ and the average magnetic induction $\mathbf{B}$ [9]:

$$\mathbf{E} = -\mathbf{v}_L \wedge \mathbf{B} \,. \tag{4}$$

In Fig. 2, we have verified that (4) is satisfied, by varying the value of the magnetic field B and also by varying the current (and hence the electric field in the sample, which was measured with a pair of voltage contacts). In the inset in Fig. 2, one can see that $v_L = E/B$.

If we limit ourselves to measuring the *average* vortex speed in the sample, then our method is a rather complicated way of measuring flux line speeds, which may be more quickly and accurately determined with a voltmeter, assuming the validity of (4). However, the main interest of our setup is to detect any variance in vortex velocities. The situation that was studied in Figs. 1 and 2 was a very clean sample in which the I-V characteristic is linear as shown in Fig. 3a, even at very low FLL velocities close

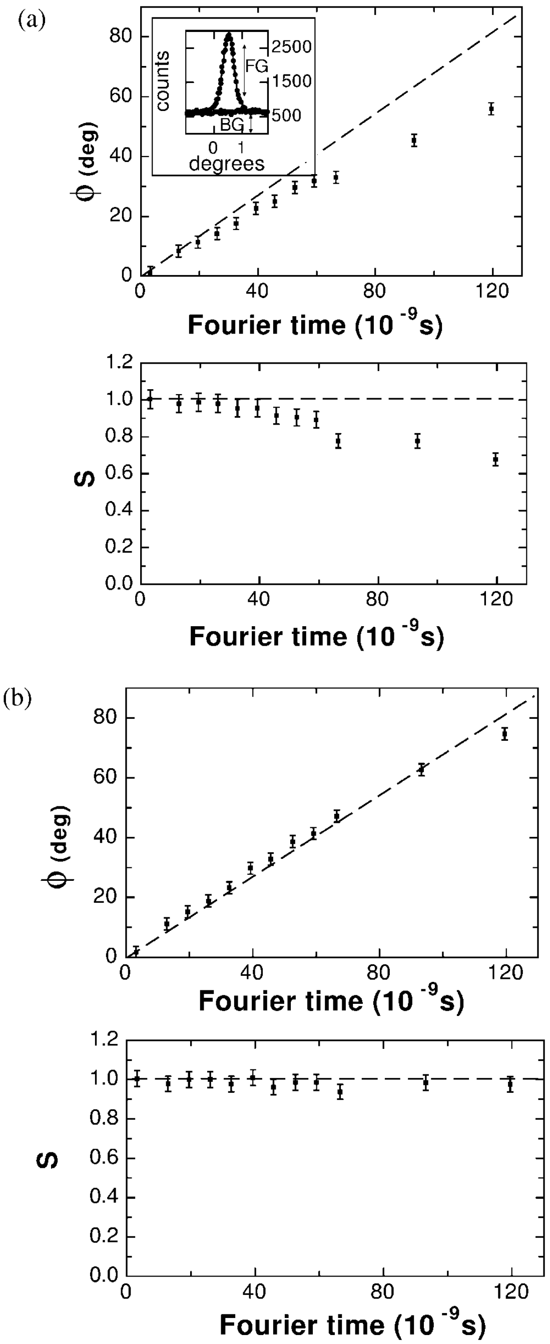

FIG. 1. (a) The phase and the amplitude of the spin echo measured at 2.2 K, 0.3 T, 12 A as functions of the Fourier time without any corrections. The dashed lines are guides for the eye. In the inset is shown a typical rocking curve for the diffraction signal from the FLL as the sample was rotated through the Bragg condition, together with the background signal measured at 10 K. These results were obtained with the sample in He gas (0.2 T, 2.8 K, 7.5 A) to avoid any change in background on heating to 10 K; in all other measurements with liquid helium present, the background intensity was established from the wings of a rocking curve. (b) The same data after subtraction of the background signal.

to the critical current. Such an *I*-*V* characteristic implies that the critical current density is very homogeneous and the vortex lattice velocity is also very homogeneous. This was checked directly by measuring the voltage at different places on the sample. In this case, the echo amplitude is a constant versus Fourier time (Fig. 3a).

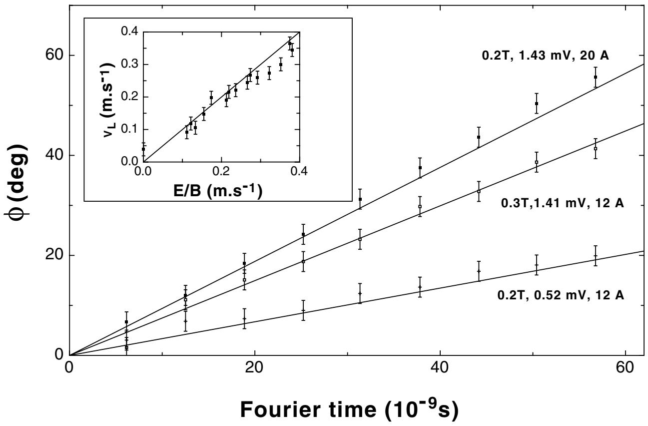

FIG. 2. The phase of the echo as a function of the Fourier time at temperatures 2.2–2.5 K for different experimental conditions of magnetic field and of voltage (measured between two contacts spaced 24 mm along the long axis of the sample). The lines are the calculated values of ϕ if v_L and E/B are equal. (To obtain the correct calibration of the Fourier time and hence the value of the slope of a line, one has to allow for the range of 15% of the wavelength of the incoming neutrons [10].) Inset: The vortex lattice velocity is shown as a function of the ratio E/B, obtained varying the current at a fixed magnetic induction of 0.3 T, showing the equality between v_L and E/B.

In the case of high T_c superconductors, it is often proposed that the vortex velocities are very inhomogeneous over short distances (a few intervortex spacings) [11]. This should be seen directly in the amplitude of the echo, as is the case in spin-echo measurements on liquids [7]. In order to test the principles of such a measurement, we have modified the sample by cutting the edges in a zigzag shape. The result (Fig. 3b) was a nonlinear *I*-*V* characteristic, typical of a nonhomogeneous critical current [12]. In this case, the echo amplitude decreases as a function of the Fourier time (Fig. 3b) as expected.

If one assumes that there is a distribution of critical currents and therefore of vortex velocities in different regions of the sample with a distribution $p(v_L)$, the amplitude S of the echo is

$$S(t) = \left| \int \exp(i\mathbf{q} \cdot \mathbf{v}_L t) p(v_L)\, dv_L \right|, \tag{5}$$

which is the Fourier transform of the function $p(v_L)$. By fitting the data in Fig. 3b with a Gaussian, and applying an inverse Fourier transform, one may obtain an estimate of the width of the distribution of vortex speeds which, within errors, is independent of v_L, and has a standard deviation $\delta v_L = 0.027\ \mathrm{ms}^{-1}$. This result suggests other interesting geometries with nonuniform flux flow to investigate, such as the Corbino disk.

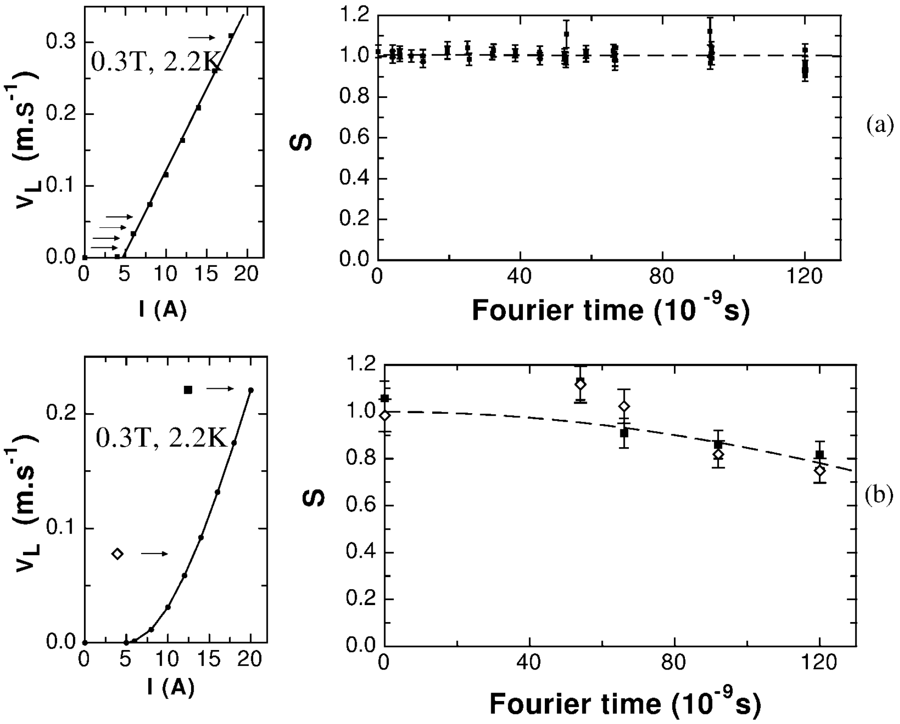

FIG. 3. (a) A voltage versus current characteristic curve of the sample showing the linearity in the flux flow regime. For the five cases marked by arrows on the characteristic, the amplitude of the spin echo versus Fourier time is shown. (b) After cutting the sample, the V-I characteristic is not linear, and for the two cases marked by arrows the corresponding echo amplitude S is not constant as a function of Fourier time. The dashed line represents the prediction of Eq. (5) for a Gaussian distribution of vortex speeds, as described in the text.

In conclusion, we were able to observe directly the movement of vortex lines by measurement of the Doppler effect on a diffracted neutron beam. In the case of a nonhomogeneous velocity, we were also able to observe this inhomogeneity. This opens a new and promising field of investigations of moving vortex lattices. To apply this to high T_c superconductors, the difficulties will be the very small intensities (the London length is long) and the very small vortex velocities which are at the present time out of the available range in IN15. However, we can envisage other questions in the important field of vortex flow and pinning effects, which can be investigated with this new technique.

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