Vortex motion in type-II superconductors probed by muon spin rotation and small-angle neutron scattering

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We report muon spin rotation (μSR) measurements on the moving vortex lattice (VL) in the type-II superconductor Pb-In, backed up by small-angle neutron scattering (SANS) observations on the same sample. We observe a motional narrowing of the μSR lineshape $p(B)$ and by SANS, alignment of the VL to the direction of vortex motion. We have calculated the μSR lineshape expected with a range of orientations of the moving VL. We demonstrate how the new μSR results give information on the moving VL which is complementary and consistent with the SANS data.

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We report here the observation of the effects of flux line motion on the muon spin rotation signal in the mixed state of a type-II superconductor. We relate the magnetic field probability distribution $p(B)$ [also known as the muon spin rotation (μSR) line shape] to the flux structure while in motion.

It is well known that when a transport current is applied to a type-II superconductor in the mixed state, the vortex lattice (VL) can break free from pinning and move in the direction of the Lorentz force.[1] The moving VL is a very interesting nonequilibrium system, exhibiting a variety of dynamical phases as a function of temperature, disorder, driving force, and applied magnetic field. It has been extensively studied theoretically[1–4] and by computer simulations[5–9] which are of particular interest because they predict an ordering and alignment of the VL *caused* by flux flow. Early experiments[10] saw no sign of alignment but recent small-angle neutron scattering (SANS) data do show this effect.[11] Our measurements represent a new microscopic technique for providing information about the moving VL on the scale of the flux line spacing. In this paper, we demonstrate this technique by detailed μSR measurements on the moving VL in a type-II superconducting alloy PbIn. First we briefly describe the μSR technique, as used to probe the mixed state of type-II superconductors and other magnetic systems. Our experimental results are then presented, followed by a comparison with our theoretical calculations as well as with recent SANS data[14] obtained from the moving VL in the same sample.

In a typical muon spin rotation experiment, the main aim is to determine the magnetic field probability distribution $p(B)$ from the (complex) polarization $P^+(t)=P_x+iP_y$, which represents the precession of the muon spins in a field in the z direction.[15,16] Positive muons, produced naturally spin-polarized by pion decay, are implanted into the specimen, and each muon spin precesses in the local magnetic field at a frequency $\omega=\gamma_\mu B$, where $\gamma_\mu=8.513\times10^8$ rad s^{-1} T^{-1} is the muon gyromagnetic ratio. Positrons emitted due to the decay of the muons (lifetime $\tau_\mu\approx2.2$ μs) are detected. Measurement of both the direction of positron emission as well as the time between muon implantation and positron detection provides a direct measure of ω, since the emitted positron emerges predominantly along the direction of the muon spin at the moment of decay.

In the mixed state of a type-II superconductor, the muons are implanted at random positions in a magnetic field distribution $B(\mathbf{r})$. Hence, $P^+(t)=P^+(0)\langle e^{i\gamma_\mu B(\mathbf{r})t}\rangle_{\mathbf{r}}$, where $\langle\cdots\rangle_{\mathbf{r}}$ denotes an average over a VL unit cell. During flux-flow, the magnetic field becomes a function of time. For a VL moving as a whole with velocity $\mathbf{v}$ past a fixed muon, we have

$$P^+(t)=P^+(0)\left\langle \exp\left(i\gamma_\mu\int_0^t B(\mathbf{r}-\mathbf{v}\tau)d\tau\right)\right\rangle_{\mathbf{r}}. \qquad (1)$$

The magnetic field probability distribution $p(B)$ is then given by the (real) Fourier transform of Eq. (1):[15]

$$p(B)=\mathrm{Re}\left\{\frac{\gamma_\mu}{\pi P^+(0)}\int_0^\infty P^+(t)e^{-i\gamma_\mu Bt}dt\right\}. \qquad (2)$$

It is possible to determine $p(B)$ directly from μSR $P^+(t)$ data using a Fourier transform or by means of a more sophisticated maximum entropy technique.[17] We used the latter as it has several advantages over the conventional technique.

The experiments reported here were carried out at ISIS, Rutherford-Appleton Laboratory, where the μSR beamline provides pulses of longitudinally polarized muons. The sample was a polycrystalline $Pb_{0.8}In_{0.2}$ alloy; the alloy ingot was made by melting a mixture of pure Pb and In in a Pyrex tube, in an atmosphere of purified argon. The ingot was then quenched in air and subsequently annealed for 300 h at 270°C under Ar.

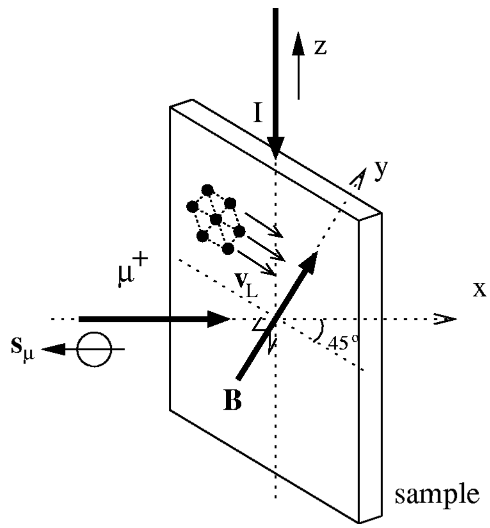

FIG. 1. Schematic diagram of the experimental setup used in the μSR measurements.

Annealing increases sample homogeneity and reduces bulk pinning. The specimen was then spark-cut from the ingot and chemically polished in order to remove residual traces of oxidation, resulting in a shiny surface with very low surface pinning.[12,13]

The sample had dimensions $20\times30\times1$ mm^3 and was placed at 45° to the muon beam and the applied magnetic field, which was perpendicular to the incoming muon momentum (Fig. 1). Since the muon spin is antiparallel to its momentum, the above arrangement ensures that the magnetic field is perpendicular to the muon spin, and at the same time maximizes the sample area "seen" by both the muon beam and the magnetic field. Transport current was applied along the long dimension of the sample, at right angles to the magnetic field and the muon beam, giving rise to vortex motion. Current was fed to the sample using superconducting wires soldered across its ends. Anhydrous antiferromagnetic Fe_2O_3 was placed around the sample in order to depolarize muons missing the sample. We used pulsed transport currents up to 80 A with an applied magnetic field of 30 mT. The current pulses were 20μs wide and were synchronized with the muon pulses which were approximately 80 ns long, repeating every 20 ms. The use of pulsed currents reduced average ohmic heating and also enabled us to check that there was negligible heating of the sample during the current pulse, which we could shift relative to the muon pulse. We found that the muon precession spectrum was only affected when the muons were in the sample at exactly the same time as the current pulses. Hence, the changes in $p(B)$ as a function of the transport current can be attributed to vortex motion alone.

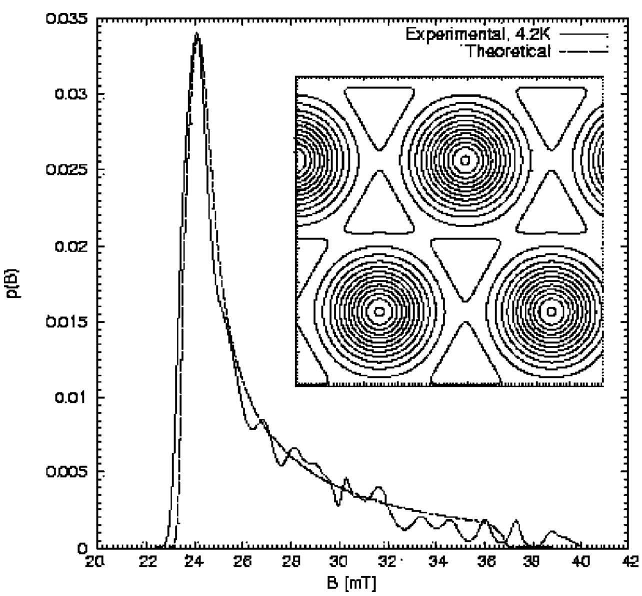

FIG. 2. Experimental and theoretical $p(B)$ line shapes corresponding to a stationary VL. The theoretical curve (dashed line) has been obtained from a solution to the full Ginzburg-Landau equations for $\kappa=5.2$ and $b=\overline{B}/B_{c2}=0.1$, where $B_{c2}=270$ mT at 4.2 K, using a method developed by Brandt (Ref. 18). The value of κ was chosen to give agreement between the two line shapes. Due to finite sample magnetization, this gives $\overline{B}\sim27$ mT for an applied field of 30 mT.

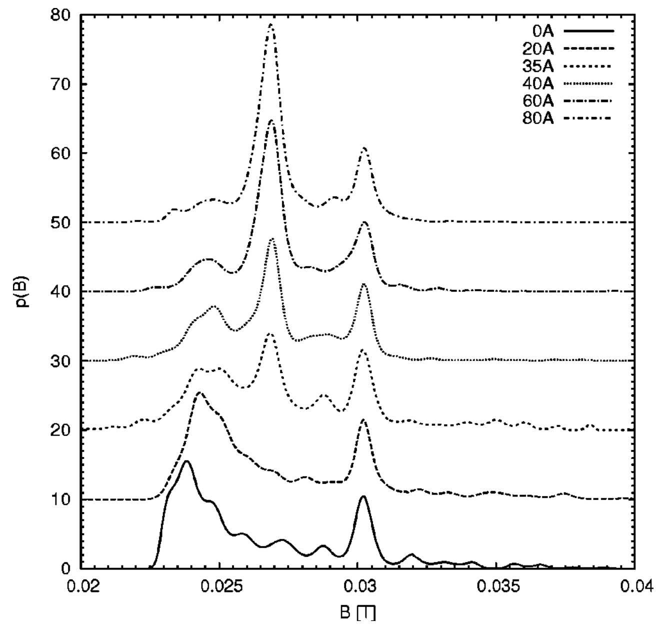

FIG. 3. Maximum entropy-fitted μSR $p(B)$ line shapes for a range of applied currents at 30 mT and 4.2 K. The peak at approximately 30 mT arises from muons stopping in the sample cryostat. This background peak has been subtracted from the data shown in Fig. 2.

Figure 2 shows a maximum entropy fit to $p(B)$, obtained using μSR $P^+(t)$ data in the absence of a transport current (i. e., stationary VL). Also shown is the line shape obtained from a solution to the full Ginzburg-Landau (GL) equations using a method developed by Brandt.[18] Figure 3 shows maximum entropy fits to μSR spectra for a range of applied currents at 30 mT and 4.2 K. It can be seen that as the vortices move faster, motional narrowing of $p(B)$ occurs, i.e., muons experience an effective magnetic field closer to the average field. At extremely high vortex velocities, the magnetic field

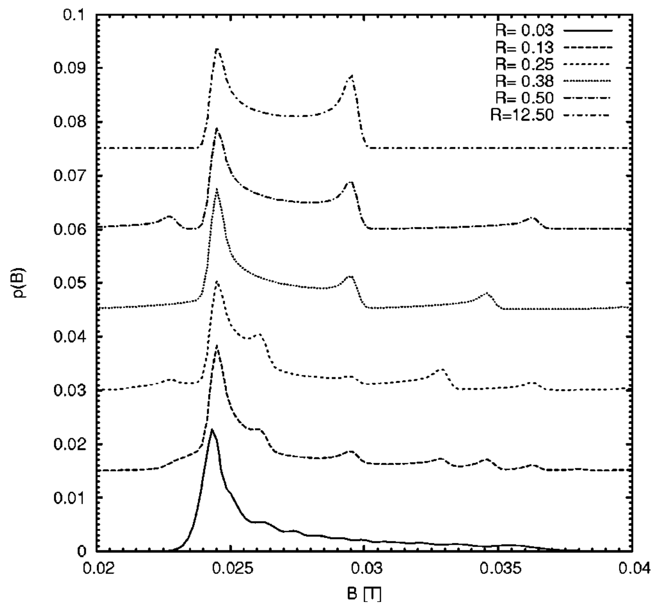

FIG. 4. Calculated $p(B)$ for a moving VL, assuming that the VL moves as a whole along a vortex nearest-neighbor direction, with a single orientation. Small "side-band" peaks are due to modulation of the muon precession frequency.

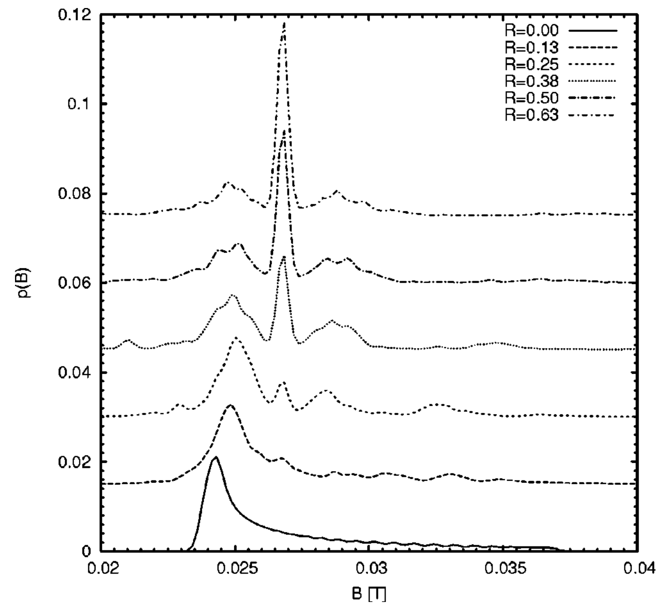

FIG. 5. Calculated $p(B)$ for a moving VL, assuming a uniformly distributed set of orientations of the VL present, each moving as a whole with a well-defined velocity.

in the mixed state is almost completely averaged out, tending to give a delta function $\delta(B-\overline{B})$, where $\overline{B}$ is the average magnetic field. However, as we now show, this result is not a *necessary* consequence of flux line motion.

To interpret these results, we have performed a general numerical implementation of Eq. (1). In this, we averaged over 10^4 initial muon positions in the VL unit cell, and $B(\mathbf{r})$ within the unit cell was given by the solution to the GL equations that fitted our static VL μSR results in Fig. 2. Since μSR is not sensitive to times much longer than the muon lifetime τ_μ, we multiplied $P^+(t)$ by a Gaussian apodization factor of the form $\exp(-t^2/2\sigma^2)$. The *apodization time* σ was set to a few times the muon lifetime. The minimum width of the $p(B)$ produced by the calculation is inversely proportional to the apodization time. After obtaining $P^+(t)$, we used Eq. (2) to calculate $p(B)$.

The direction of the VL velocity, as expected from experiments,[11] theories[3,4] and simulations[5–8] is parallel to a nearest-neighbor direction. In Fig. 4 we show the numerically calculated $p(B)$ assuming that the VL is moving as a whole with a single, well-defined velocity. The quantity R is a dimensionless measure of the vortex velocity and is given by $R=2\pi|\mathbf{v}|/(\gamma_\mu a_0 \Delta B)$, where $\Delta B \equiv \max\{B(\mathbf{r})\} - \min\{B(\mathbf{r})\}$ and a_0 is the vortex spacing. Thus, R represents the ratio of the frequency with which the VL unit cells pass the muon, to the spread of precession frequencies within a VL unit cell. In Fig. 4, we predict at large R a characteristic two-peak line shape, without the central peak seen in the data. The two peaks arise because motional narrowing is never complete. Instead, the time-averaged field at large R is a one-dimensional distribution, with the maximum field along lines where the VL cores pass, and minimum field in between. The two peaks in $p(B)$ are at the values of this maximum and minimum field. Comparison of these line shapes with the quite different ones shown in Fig. 3 leads to the conclusion that on the time scale of the muon lifetime, the vortices do *not* move exactly in a single, VL nearest-neighbor direction.

We have therefore taken our simulation to the opposite limit, and averaged equation (1) over all angles between the VL nearest-neighbor direction and the direction of vortex motion, which gives the results shown in Fig. 5. It can be seen that the calculations exhibit all the characteristic features of Fig. 3, with the development at high currents of a peak at the average field position (which is 27 mT) and two broad satellites on either side [these satellites reflect contributions to $p(B)$ from VL motion nearly parallel to a VL lattice vector]. These theoretical results appear similar to those obtained by Delrieu for the case of NMR line shape in the moving mixed state.[10] However, his numerical evaluation of the exact calculation was restricted to near H_{c2} and he incorrectly calculated the power spectrum of the field distribution instead of $p(B)$. His experimental results, on a very thin foil, are similar to Fig. 3 and were interpreted as being due to a uniformly distributed set of orientations of the moving VL. Nonetheless, there *is* an alignment of the moving VL in our thicker samples, as shown by small-angle neutron scattering (SANS) experiments on a polycrystalline sample with steady vortex motion.[11]

In order to show how sensitive our theoretical predictions are to VL orientation, we generalized our model to include a normally-distributed range of orientations of the VL, with angular probability density given by

$$f(\theta;\sigma_\theta) \propto \sum_{n=1}^{6} \left(e^{-(\theta-2n\pi/6)^2/2\sigma_\theta^2}\right), \tag{3}$$

where θ is the angle between a VL principal direction and the direction of VL motion and σ_θ represents the width of the distribution. For $\sigma_\theta=0.2$ the resulting $p(B)$ line shapes are essentially identical to the ones shown in Fig. 5. For $\sigma_\theta < 0.1$ rad the $p(B)$ line shapes begin to exhibit some of the

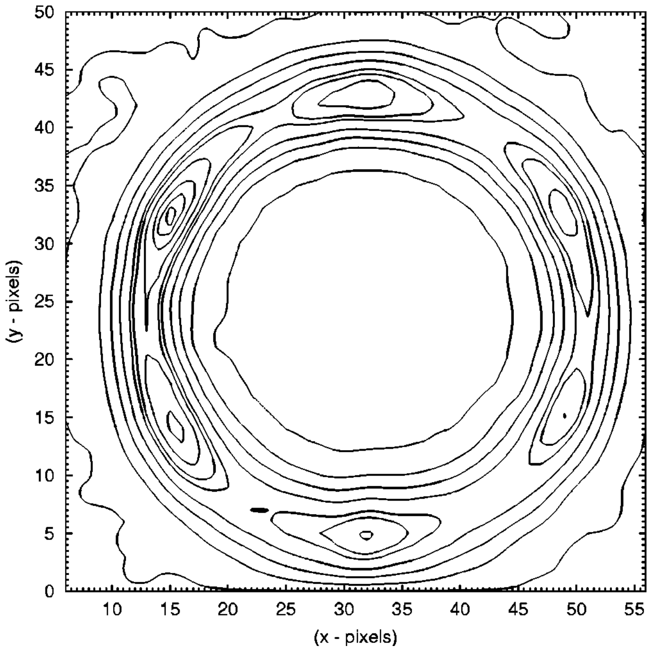

FIG. 6. Small-angle neutron diffraction pattern obtained from a polycrystalline Pb-In sample, for a pulsed transport current of 80 A, temperature of 4.2 K, and 50 mT applied magnetic field. The current pulse width was 20μs at a frequency of 50 Hz. The sample was placed at 45° to both the neutron beam and the applied magnetic field.

features of those shown in Fig. 4. Thus the μSR technique is sensitive to a small amount of angular disordering of the VL flow.

In order to determine whether this could be a resolution of the apparent discrepancy, we carried out SANS experiments on our μSR sample, under similar experimental conditions. Figure 6 shows the neutron diffraction pattern from the VL as ''frozen'' in the sample from its moving state, created by a pulsed transport current. Our SANS measurements suggest that the moving VL exhibits a *range* of orientations with respect to the direction of motion. Analysis of the data shows that there is an extra transverse width of 0.2 rad (rms) in addition to the resolution-limited finite radial and transverse widths of the Bragg peaks.[19] This extra transverse width is believed to correspond to a range of VL orientations present during flux flow, thus confirming the misalignment indicated by our μSR results.

Calculations[4,9] suggest that in a weakly disordered three-dimensional superconductor (such as our Pb-In alloy), the vortices flow, *on average*, along well-defined static channels which are elastically coupled. Depending on the roughness of these channels, the moving VL system would then appear to be topologically ordered, giving rise to six diffraction peaks, the intensity-spread of which is an indication of the channel roughness. On a small time scale (such as the muon lifetime) an implanted muon would then sample the channel roughness as multiple orientations of the VL, leading to the $p(B)$ spectra shown in Fig. 3. It is certainly clear that in our experiment on a real three-dimensional (3D) system the VL does not move as a completely orientationally aligned solid, as suggested by many theoretical results.[3,4,6,7] It would be of great interest to carry out experiments on more nearly two-dimensional (2D) systems using low-energy muons.[20] We expect that future work using our technique will enable further details of vortex motion, such as the correlation function for the local vortex velocity, to be obtained in suitable systems.

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[1] P. Nozieres and W.F. Vinen, Philos. Mag. **14**, 667 (1966).
[2] J. Bardeen and M.J. Stephen, Phys. Rev. **140**, A1197 (1965).
[3] A.E. Koshelev and V.M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).
[4] P. Le Doussal and T. Giamarchi, Phys. Rev. B **57**, 11356 (1998).
[5] D.W. Braun, G.W. Crabtree, H.G. Kaper, A.E. Koshelev, G.K. Leaf, D.M. Levine and V.M. Vinokur, Phys. Rev. Lett. **76**, 831 (1996).
[6] S. Spencer and H.J. Jensen, Phys. Rev. B **55**, 8473 (1997).
[7] C.J. Olson, C. Reichhardt, and F. Nori, Phys. Rev. Lett. **81**, 3757 (1998).
[8] A. van Otterlo, R.T. Scalettar, G.T. Zimányi, R. Olsson, A. Petrean, W. Kwok, and V. Vinokur, Phys. Rev. Lett. **84**, 2493 (2000).
[9] K. Moon, R.T. Scalettar and G.T. Zimányi, Phys. Rev. Lett. **77**, 2778; S. Ryu, M. Hellerqvist, S. Doniach, A. Kapitulnik, and D. Stroud, *ibid.* **77**, 5114 (1996).
[10] J.M. Delrieu, J. Phys. F: Met. Phys. **3**, 893 (1973).
[11] C. Goupil, A. Pautrat, C. Simon, P.G. Kealey, E.M. Forgan, S.L. Lee, S.T. Johnson, G. Lazard, B. Placais, Y. Simon, P. Mathieu, R. Cubitt, and C. Dewhurst, Physica C **341**, 999 (2000).
[12] J.D. Livingston, Phys. Rev. **129**, 1943 (1963).
[13] D.E. Farrell, B.S. Chandrasekhar, and H.V. Culbert, Phys. Rev. **177**, 694 (1969).
[14] D. Charalambous, ILL Experimental Report No. 5-32-611 (2000).
[15] E.H. Brandt, Phys. Rev. B **37**, 2349 (1988).
[16] S.L. Lee, in *Muon science*, edited by S.L. Lee, S.H. Kilcoyne and R. Cywinski (Institute of Physics, Bristol, 1998), p. 149.
[17] T.M. Riseman and E.M. Forgan, Physica B **289**, 718 (2000).
[18] E.H. Brandt, Phys. Rev. Lett. **78**, 2208 (1997).
[19] R. Cubitt, E.M. Forgan, D.McK. Paul, S.L. Lee, J.S. Abell, H. Mook, and P.A. Timmins, Physica (Amsterdam) **180**, 377 (1992).
[20] C. Niedermayer, E.M. Forgan, H. Glückler, A. Hofer, E. Morenzoni, M. Pleines, T. Prokscha, T.M. Riseman, M. Birke, T.J. Jackson, J. Litterst, M.W. Long, H. Luetkens, A. Schatz, and G. Schatz, Phys. Rev. Lett. **83**, 3932 (1999).