Atomic-Beam Observations of the Magnetic Field Outside a Type-II Superconductor*

Truman R. Brown and John G. King
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 4 December 1970)

We describe a new method for observing magnetic periodicities, both spatial and temporal, ultimately capable of resolving wavelengths between 100 and 10^5 Å and frequencies between 0.5 and 500 MHz. We have used this method to observe the periodic magnetic field above the surface of a type-II superconductor containing a lattice of flux lines which moves under transport currents. We believe that the measurements are the first direct observations of the flux-flow velocity in a type-II superconductor.

We have developed a new method for studying periodic magnetic fields. We observe the relative transition probability between two of the hyperfine states in a state-selected beam as a function of atomic velocity, after the beam has passed through the periodic magnetic field to be investigated. By Galilean invariance a magnetic field of spatial wavelength d will appear in the rest frame of the atoms as a time-varying field of frequency v/d, where v is the velocity of the atom. Whenever the frequency v/d is equal to the frequency of a transition between two of the hyperfine states, the transition probability will increase. In the case of a type-II superconductor, this can be expressed formally in terms of the reciprocal lattice vectors of the two-dimensional vortex lattice, each reciprocal lattice vector (corresponding to a particular spatial wavelength in a particular direction) giving rise to one peak in the transition probability.

A time variation can be observed as a change in the curve of transition probability versus velocity. In particular, the velocity of the vortex lattice, when parallel to the atomic velocity, merely causes the curve to shift in velocity by an amount equal to the lattice velocity.

Figure 1 is a schematic diagram of the apparatus. It is a standard atomic-beam magnetic-resonance apparatus[1] with the usual interaction region replaced by the superconducting foil. The velocity distribution of the collimated potassium beam is measured by chopping the beam with a slotted wheel and using time-of-flight analysis. The inhomogeneous field of the A magnet focuses atoms in a particular state of m_j in such a way that they pass over the superconducting foil attached to a He Dewar. A brass knife edge, set 0.0002 in. away from the foil, collimates the beam at this point. A uniform transverse magnetic field can be applied to the foil. The supporting structure for the foil is constructed of nonmagnetic materials. The beam then enters the inhomogeneous field of the B magnet which refocuses only those atoms which have undergone transitions to the opposite m_j state onto a hot-wire ionizing detector. The resulting ions are amplified by an electron multiplier and pulse amplifier and counted and stored in a multichan-

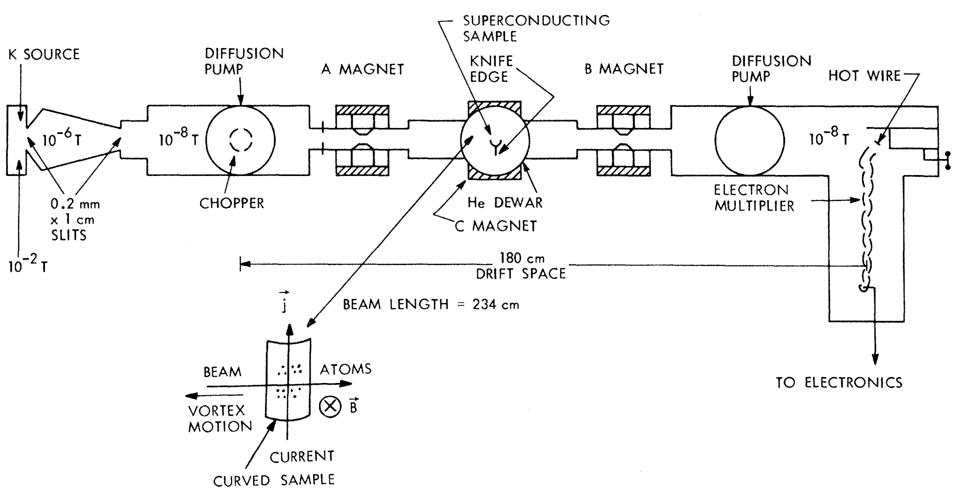

FIG. 1. Top view of the apparatus.

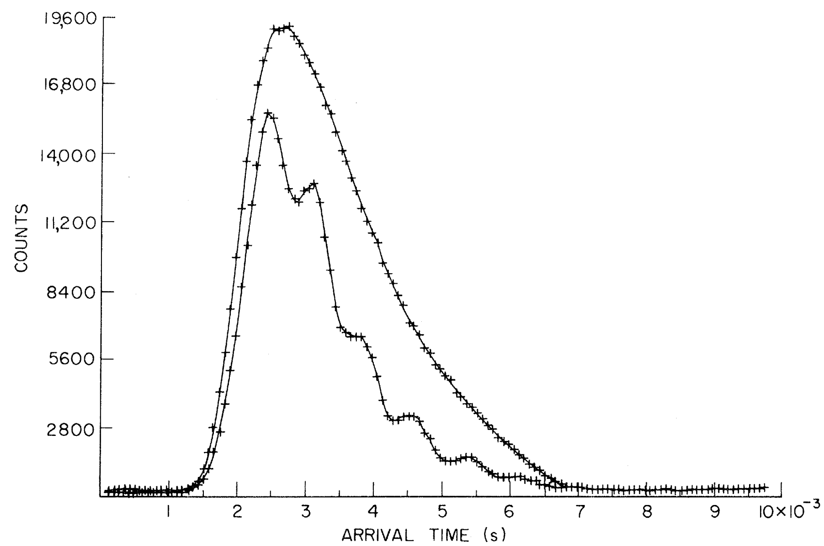

FIG. 2. Accumulated counts versus arrival times of atoms which have undergone transitions. In the upper curve transitions were induced by an oscillating field in order to determine the velocity distribution of the atoms passing the foil. In the lower curve transitions were induced by the magnetic field outside the superconducting foil at 4.2°K and in an external field of 2.6 G. Each curve represents a counting interval of 1 min.

nel scaler (MCS) according to their arrival time.

The following results are from an annealed vanadium foil with a resistance ratio of 70. The foil is $0.0125\times1\times1.8$ cm^3. It is bent along the long axis to a radius of approximately 2 cm in order to reduce any edge effects and to avoid alignment difficulties. We do not expect that this slight curvature has any significant effect. The current (from zero to approximately 1.5 A) was supplied by a wire spot welded to one corner, the ground return being through the stainless-steel Dewar. An alternating current was derived synchronously from the chopper so that the current direction would alternate every other beam pulse. The phase of the current was adjusted so that the maximum current occurred when the pulse of atoms passed the foil. By varying the magnetic field (at fields less than 5 G) at the same time that a current was flowing through the sample, in roughly $\frac{1}{4}$ of the attempts, curves similar to the lower curve in Fig. 2 were obtained after the current was shut off. In the other cases broad peaks which were independent of current were observed. If the field were increased when the multiple peak structure was present, then there would be no effect for changes of the order of 1 G, but for larger increases (above 5 G) the multiple peaks would suddenly disappear. It is this multiple peak structure which is consistent with the Fourier components seen by the moving atoms that establishes that the transitions must arise from the vortex lattice.[2]

The velocity distribution of the atoms passing the superconductor was determined by inducing transitions in the standard way with an oscillating magnetic field (the upper curve in Fig. 2). It was then possible to obtain the relative transition probabilities for atoms of a given velocity passing throught the field outside the superconductor, as shown in the middle curve of Fig. 3, in which the lower curve in Fig. 2 has been divided, channel by channel, by the upper curve in Fig. 2 and then plotted against the velocity corresponding to the midpoint of each channel. These data can be qualitatively explained by a regular vortex lattice in the foil. Both the size and the spacing are what would be expected for our fields. Unfortunately, because of the unknown internal field, the unknown orientation of lattice, and the many possible reciprocal lattice vectors which can cause transitions, a quantitative discussion is not possible.

When an alternating current was passed through the foil, the upper and lower curves in Fig. 3 were obtained after normalizing to get the relative transition probability. Although the reasons for the loss of structure at high and low velocities for opposite current directions are not yet understood, the spacing of the remaining peaks of the two curves clearly indicates a constant shift in velocity. This must result from a Doppler shift of the moving vortex lattice[3] with respect to the atoms in the beam. Translating the

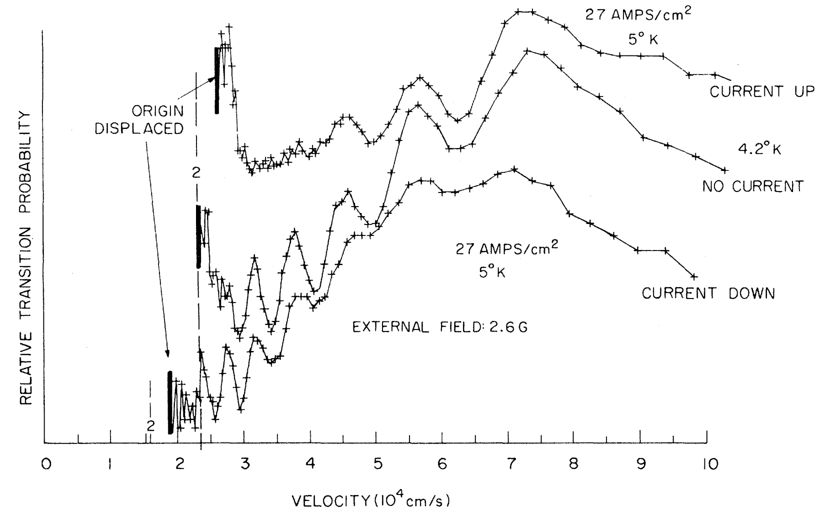

FIG. 3. Relative transition probability versus atomic velocity for various current conditions. The field direction was the same as that indicated in the insert of Fig. 1.

curves horizontally brings this shift clearly into view. (The curves have been shifted vertically for clarity.)

Two convincing indications that these data are real and due to the superconductor are the lack of any signal when the temperature is raised above T_c and the disappearance of the shift when the alternating current is phase shifted so that the current through the foil is zero rather than the maximum when the atoms pass. Unfortunately, because of difficulties with the temperature control, it was not possible to determine exactly the temperature at which the signal vanished.

A plot of the constant shifts versus the current amplitude through the foil for a typical case (Fig. 4) shows a pattern very similar to that of the voltage-current curves measured in flux-flow experiments.[4] In order to compare these data with the macroscopic flux-flow measurements, dv/dj was computed from the equations

$$\eta v = j\varphi_0/c - F_p,$$

$$\vec{E} = \vec{v}\times\vec{B}/c,$$

$$\rho_f = \rho_n(B/H_{c2}),$$

where φ_0 is the flux quantum, F_p is the pinning force, and η is the viscosity limiting the flow velocity. This leads to the relation $dv/dj = \rho_n c/H_{c2}$. The slopes predicted by this equation are approximately a factor of 1000 smaller than the slope in Fig. 3.

In an attempt to understand this disagreement a series of voltage-current characteristics were then measured at 4.2°K in a different apparatus on the same curved foil in various uniform transverse magnetic fields from 0 to 900 G. These characteristics were independent of magnetic field strength although their appearance was similar to the characteristics given in the literature.[4] As yet we have no explanantion for their independence with respect to magnetic field. However, if the relation $\rho_f = \rho_n(B/H_{c2})$ is not used in the above derivation for dv/dj, we obtain the following equation:

$$\rho_f = dE/dj = (dE/dv)dv/dj = (B/c)dv/dj.$$

Using the measured values of ρ_f and dv/dj, we find that internal fields of 0.5 to 2 G will satisfy this equation, depending on exactly how ρ_f is chosen. This is in reasonable agreement with our external field. Because of the uncertainty in lattice orientation this entire field range (cor-

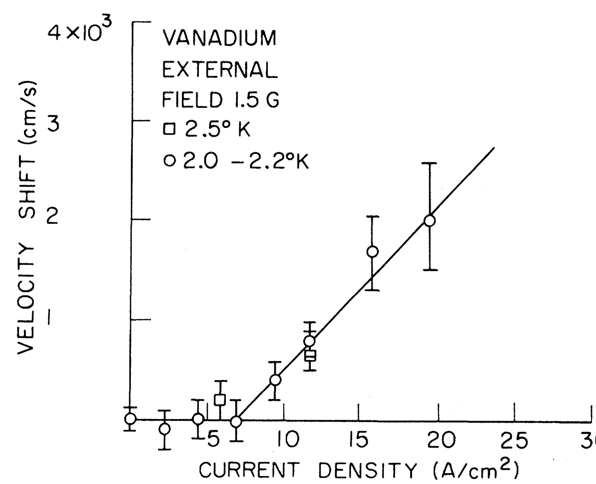

FIG. 4. Constant velocity shift versus current density.

responding to vortex spacings of 6.8 to 3.4 μm) is consistent with the above peak structure.

Thus on the present sample both the microscopic measurements with the atomic beam and the macroscopic measurements with the voltage probes indicate that the expression $\rho_f = \rho_n(B/H_{c2})$ is not valid. However, the more fundamental relation $\vec{E} = \vec{v} \times \vec{B}/c$ which is not measured by the macroscopic measurements is consistent with the microscopic data.

Future measurements in which both the voltage drop across the sample and the internal magnetic field are measured *in situ* should allow us to investigate further some of the questions which the present experiments raise but do not answer. These include the washing out of the peaks in the relative transition probability when a current is flowing, the independence of the resistivity to magnetic field, the lack of signals at higher fields, and the occasional nonconstant velocity shift when a current is flowing. This latter should be particularly interesting since the probable explanation is a large Hall voltage which causes the lattice to flow at an angle to the atomic beam. In addition, we plan to observe samples for which the expression $\rho_f = \rho_n(B/H_{c2})$ is valid. We hope these experiments will allow a microscopic check of the present theories of flux flow.

In conclusion, we feel that the first application of this method demonstrates some of its inherent possibilities. For example, merely by changing our beam from potassium to cesium we should be able to observe periodicities down to 100 Å. Further applications might include the study of how vortices are created and destroyed at the edges of a superconductor, possible collective motions of the vortex lattice, fluctuations near the Curie point in a ferromagnet, domain boundary motion in ferromagnets, etc. A further possibility would be to observe electric fields in much the same manner using a beam of molecules which are sensitive to oscillating electric fields.

We acknowledge the assistance of Professor R. M. Rose for lending us the necessary equipment to measure the voltage-current characteristics of the foil, and of Dr. A. G. Redfield who gave us the vanadium sample from a larger amount supplied to him by Mr. T. A. Sullivan of the Boulder City Metallurgy Research Laboratory of the U. S. Bureau of Mines.

*Research sponsored in part by Joint Services Electronics Program Contract No. DA28-043-AMC-02536 (E) and in part by the Massachusetts Institute of Technology Sloan Fund for Basic Research.

[1]For a general reference on atomic beam techniques see N. F. Ramsey, *Molecular Beams* (Oxford U. Press, Oxford, England, 1956).

[2]U. Essmann and H. Trauble, Phys. Status Solidi 20, 95 (1967), and J. Appl. Phys. 39, 4052 (1968).

[3]For a general review of research in this area see Y. B. Kim and M. J. Stephen, in *Superconductivity*, edited by R. D. Parks (Marcel Dekker, New York, 1969), Chap. 19. See also H. Meissner, J. Low Temp. Phys. 2, 267 (1970).

[4]Y. B. Kim, C. F. Hemstead, and A. R. Strnad, Rev. Mod. Phys. 36, 43 (1964), and Phys. Rev. Lett. 12, 145 (1964), and Phys. Rev. 139, A1139 (1965), and Phys. Rev. Lett. 13, 794 (1964).

Critical Concentration Versus Interaction Range for Random Systems

H. L. Scott, Jr.
Department of Physics, University of Utah, Salt Lake City, Utah, 84112
(Received 8 March 1971)

We consider the problem of interacting particles occupying random sites on either a plane square or a simple cubic lattice. The critical concentration p_c is defined as that concentration below which the cooperative transition which normally occurs in the system can no longer take place. In this paper we obtain an expression for p_c as a function of the interaction range r, exact when $r^d \gg 1$ (d = dimensionality, r measured in units of lattice constant).

The study of the statistical behavior of interacting particles which occupy randomly a fraction p of the sites of an otherwise empty lattice is of interest for two reasons. First, the properties of such systems may shed some light on the nature of cooperative phenomena in fully occupied lattices.[1] Secondly, these random systems are related to problems involving substitutional defects in regular crystal lattices. For example, OH^- ions may replace halide ions in alka-