Scanning-Tunneling-Microscope Observation of the Abrikosov Flux Lattice and the Density of States near and inside a Fluxoid

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The Abrikosov flux lattice is imaged in $NbSe_2$ by tunneling into the superconducting gap edge with a low-temperature scanning-tunneling microscope. The tunneling conductance into a single vortex core is strongly peaked at the Fermi energy, suggesting the existence of core states or core excitations. As one moves away from the core, this feature evolves into a density of states which is consistent with a BCS superconducting gap.

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Since its inception the scanning-tunneling microscope, STM, has proven itself a promising tool in low-temperature physics. Images which show both charge-density waves and the atomic lattices have been achieved.[1] In addition to providing topographical information the STM is capable of local spectroscopy. This has been demonstrated by the direct observation of the superconducting energy gap.[2] One of the more remarkable states of a superconductor, the Abrikosov flux lattice, is accessible to a STM. New insight into the nature of type-II superconductivity may be given by an STM probe of the electronic density of states both inside and outside the flux cores.

This Letter describes how the vortex lattice is imaged and the results of a spectroscopic probe of the cores. Previously, the Abrikosov flux lattices could only be observed indirectly with Bitter patterns,[3] where fine magnetic particles were deposited on a cold superconductor to mark the position of the flux lines. That technique was constrained to relatively low magnetic fields and did not allow the observation of the dynamics of the lattice. Neutron diffraction allows the observation only at very high magnetic fields.[4] The STM, with the more direct technique of tunneling into states in the region of the superconducting gap, allows observation of the lattice under the full range of magnetic fields. Furthermore, we use the power of the STM, as a local spectroscopic tool, to observe the variation of the density of the states in and around a single flux line.

We chose $NbSe_2$ for its excellent surface quality.[1] It is observed to be clean over the entire 6000-Å scan range. $NbSe_2$ is a layered crystal that undergoes a charge-density wave transition at 33 K. High-quality STM images show both atomic resolution and charge-density waves below 10 K. These images serve as a convenient calibration for the xy deflection of the microscope tip. $NbSe_2$ is also a type-II superconductor with a T_c of 7.2 K. The upper critical field is 32 kG for a field perpendicular to the plane.

The density of states of the superconductor in the absence of an applied field was obtained from dI/dV vs V curves. These curves can be generated by ramping the tip to sample voltage with a single triangle wave from -5 to $+5$ mV. A small superimposed dither voltage of 0.1 mV rms allows one to measure the differential conductance dI/dV vs V. (The sample-to-tip distance is held steady to better than 0.03 Å during the sampling period in order to maintain a constant tunneling barrier.) The dI/dV vs V curve is plotted in Fig. 1 for the sample at 1.45 K. The differential conductance is directly proportional to the density of states in the sample. A good fit is obtained to the standard BCS functional form if one takes into account the finite (0.1 mV) amplitude of the ac modulation. We obtain a value of 1.11 ± 0.03 meV for the superconducting gap energy. This value is larger than that obtained previously from point contact measurements[5] of 0.62 meV and agrees with infrared transmission measurements[6] of 1.12 meV. The temperature dependence of the gap also agrees well with the

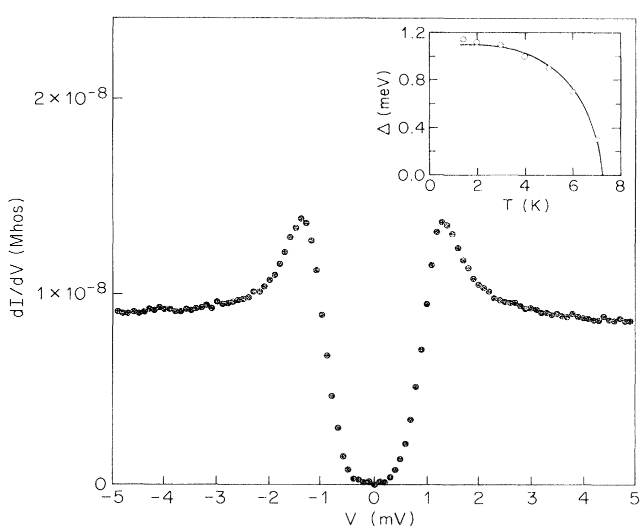

FIG. 1. dI/dV vs V for $NbSe_2$ and 0-T applied magnetic field used to determine the gap at 1.45 K. Inset: The gap vs temperature and the corresponding BCS fit.

BCS form as shown by the inset of Fig. 1.

Since $NbSe_2$ is a type-II superconductor, its density of states should be modulated by the Abrikosov flux lattice when a magnetic field is applied. To image the flux lattice, the bias voltage is reduced to 1.3 mV and the tip height is controlled to maintain a 11-pA dc tunneling current. 1.3 mV is the point of maximum differential conductance in the curve of Fig. 1. Although the differential conductance is peaked, the overall conductance (I/V) into a superconducting region should be reduced since no states contribute below the gap energy. As one scans the tip over a fluxoid with a normal core one might expect the total density of states available for tunneling to increase. The STM constant current feedback would then retract the tip slightly over any fluxoid. An image of z position of the tip over the x,y plane does clearly show the vortices. However, even better images can be achieved if one monitors dI/dV as one completes a constant dc current scan of the surface. The value of dI/dV at 1.3 mV, which is enhanced in the superconducting region, should then be reduced when tunneling into the normal core. This is the signal which is plotted on a gray scale in Fig. 2. The vortex spacing in the triangular lattice is measured to be 479 ± 2 Å, consistent with the 479.1 Å expected in a field of 1.041 T. This triangular lattice expands and survives as fields are lowered to 0.02 T. The 6000-Å scan range prevents observation of the lattice at yet lower fields.

The IV curves taken in a magnetic field are now strongly position sensitive as expected. To explore this variation, we consider isolated vortices first by reducing the field to 200 G where the spacing is 3460 Å, sufficiently large to prevent interaction and overlap effects. (The temperature is now 1.8 K.) Figure 3 shows the differential conductance traces taken at three points: directly into the core of the vortex, about 75 Å away from the core, and into a superconducting area that is equidistant, 2000 Å, from the three nearest vortices. The third dI/dV curve of the superconducting region is similar to the zero field curves of Fig. 1. As for tunneling into the center of the vortex itself, one might expect a flat density of states associated with a normal core and hence a flat featureless dI/dV. (The differential conductance is indeed observed to be flat and featureless if the sample is made normal by warming above the transition temperature.) Instead, upon tunneling into the vortex, the differential conductance is enhanced at zero bias. On tunneling 75 Å away from the vortex, we observe this zero-bias peak superimposed on the superconducting gap. If the same data are taken at 1 T, where the vortex spacing is smaller, the zero-bias peak is less pronounced and somewhat broadened.

In order to better understand the spatial variations of these features near a single vortex 128 dI/dV vs V curves were taken equally spaced along a 1000-Å line that intercepted the vortex. The temperature was 1.8 K, the applied field was 0.03 T, and V ranged from -5 to $+5$ mV. The whole data acquisition process took over an hour and before and after xy scans of the style of Fig. 2 show less than a 100-Å drift of the vortex during the V vs Y scan. The result of this spectroscopic mapping is plotted in Fig. 4 on V,Y coordinates with the vertical scale corresponding to dI/dV. The gap is visible as the canyon at the top and bottom of the figure. As one approaches the vortex, the center of the gap fills in with states and the enhanced density of states at the gap edge is eroded to the normal value. The spatial extent of the enhanced density of states at 1.3 meV is shown directly in Fig. 5, where a cut parallel to y axis of Fig. 4 at

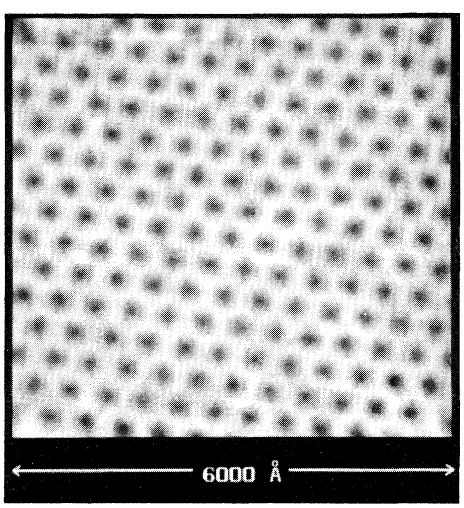

FIG. 2. Abrikosov flux lattice produced by a 1-T magnetic field in $NbSe_2$ at 1.8 K. The scan range is about 6000 Å. The gray scale corresponds to dI/dV ranging from approximately 1×10^{-8} mho (black) to 1.5×10^{-9} mho (white).

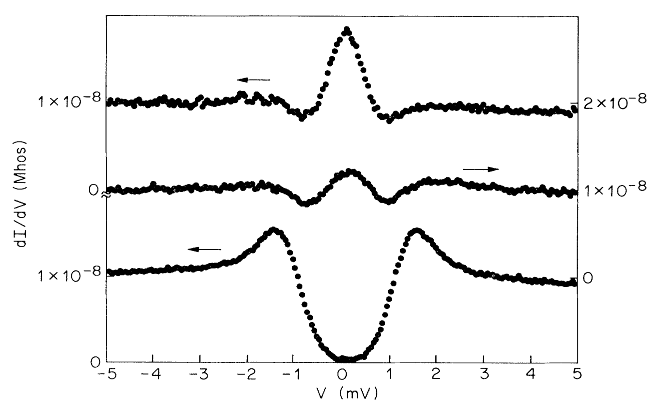

FIG. 3. dI/dV vs V for $NbSe_2$ at 1.85 K and a 0.02-T field, taken at three positions: on a vortex, about 75 Å from a vortex, and 2000 Å from a vortex. The zero of each successive curve is shifted up by one quarter of the vertical scale.

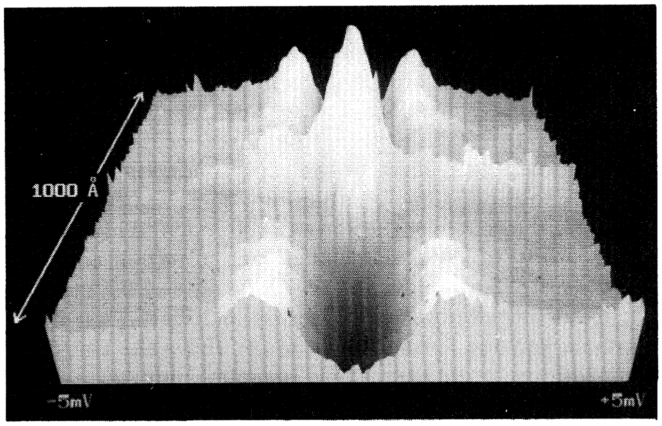

FIG. 4. Perspective image of dI/dV vs tunneling voltage (horizontal axis) and position along a line that intersects a vortex (vertical axis).

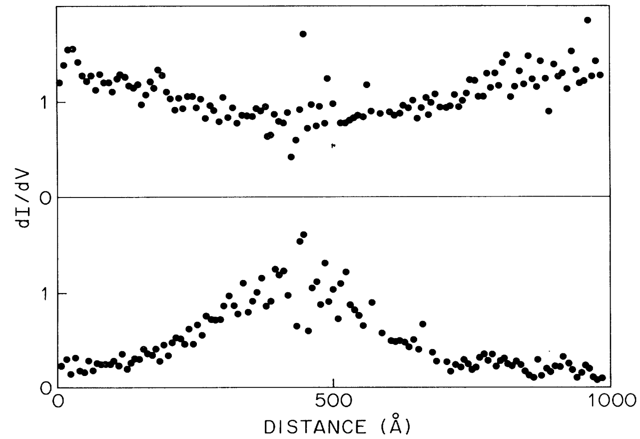

FIG. 5. Differential conductance dI/dV (arbitrary scale) at zero bias (lower curve) and at 1.3 mV (upper curve) as a function of position.

$V=1.3$ mV is displayed. At the point of closest approach, which is within 100 Å of the vortex center, the strong enhancement of the conductance at zero bias is observed. The height of the peak is very sensitive to the microscope tip position relative to the vortex. The spatial extent of the zero-bias peak can be displayed more directly by taking a cut along the y axis at $V=0$ of Fig. 4. This is also plotted in Fig. 5. The half width is of the order of 150 Å, somewhat larger than the 77-Å coherence length[7] l in the plane of the surface.

We do not have a quantitative explanation of this enhanced conductance at zero bias in the center of the vortex core. One might think of the vortex core as region of quasiparticle states that are confined radially (radius $\sim 2l = 154$ Å) by a shallow potential well approximately 1.1 meV deep.[8] Its radius may be temperature sensitive,[9] depending self-consistently on the quasiparticle occupation of states. Additional constraints are imposed on the radial motion by the charge-density wave gap (measured to be 35 meV). This confined wave function will then decay into the region around the core and its density distribution may explain the spatial extent of the zero-bias density of states. The spin degree of freedom may also be important since the spin splitting is 0.4 meV at the 3-T field of the core.

In conclusion we have measured the superconducting gap in $NbSe_2$ using an STM. By tunneling at a voltage comparable to the gap and monitoring the z position or dI/dV we have been able to image the Abrikosov flux lattice. The spatial variation of the density of states both in a 10-kG flux lattice and through relatively isolated flux lines of a 300-G field has been measured. We find an enhanced conductance near zero bias when tunneling into the vortex core. Further experiments will be required to fully explain this feature.

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Note added.— If the line of 128 points along which the data were collected did not intersect the core precisely and missed it, the measured spatial extent (Fig. 5) would be broader than the actual one. An alternate more direct STM measurement has given a half width of 77 ± 5 Å at 1.9 K.

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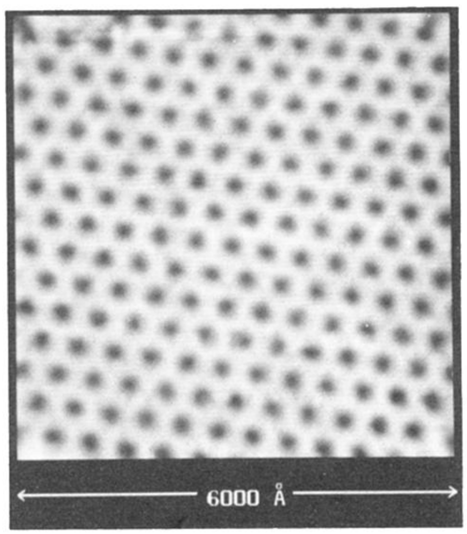

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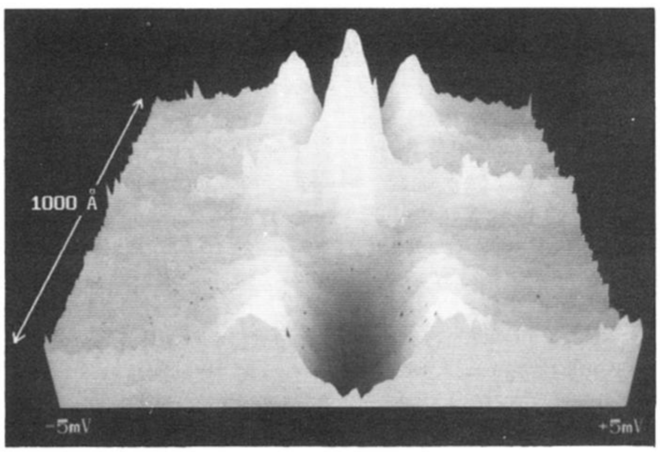

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