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Measurement of the vortex-core radius by scanning tunneling microscopy

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Using a scanning tunneling microscope operated in a spectroscopic mode we imaged flux-line lattices in niobium diselenide at various external magnetic fields. From the evaluation of a large number of tunneling-current profiles taken across the individual vortices we deduced the dependence of the vortex-core radius on the applied magnetic field. It was found that the core radius shows a pronounced decrease with increasing field, even for $H/H_{c2} << 1$. This behavior is qualitatively well characterized by self-consistent solutions of the Usadel equations.

The outstanding analytical potential of scanning tunneling microscopy (STM) is due to its inherent capability of obtaining spectroscopic information at the sub-meV level combined with a lateral resolution of the order of angstroms. This enables one to probe superconductive properties on a length scale smaller than the coherence length. The present investigations have been performed on 2H-$NbSe_2$ which is a layered type-II superconductor. It is particularly well suited for STM because the freshly cleaved surfaces are relatively inert against contamination.

The experiments have been performed with a low-temperature STM which has been described in some detail in Ref. 1. The local surface density of quasiparticle states is probed in the following way [2]: At any point on the surface the STM's feedback loop is interrupted for a short period (< 1 second), while the tunneling voltage V is decreased from beyond the superconductor's gap voltage $V_g = \Delta_0/e$ to a certain value $V_0 < V_g$. Upon raster-scanning the normal conducting tip the corresponding tunneling current $I(V_0)$ then continuously varies between an upper limit I_{max} right at the center of a vortex and a lower limit I_{min} farthest from all adjacent vortices. All present measurements have been performed at $T/T_c = 0.6$. To change the vortex spacing the external magnetic field perpendicular to the sample surface was varied within the interval $0 \leq H/H_{c2} \leq 0.3$.

Figure 1 shows a tunneling-current image of the vortex lattice at an external field of $H/H_{c2} = 0.14$. The sub-gap tunneling voltage was $V_0/V_g = 0.88$ at negative sample bias.

We systematically analyzed numerous line scans across individual vortices. The actual vortex profiles were deduced from complete images such as displayed in Fig. 1. A characteristic measure of the respective vortex-core radius is arbitrarily defined by the particular distance ρ from the vortex center

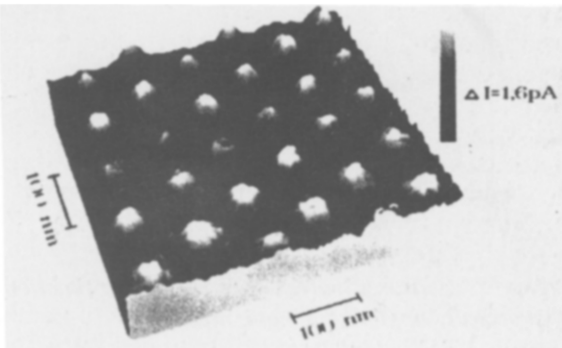

Figure 1. Typical tunneling-current image of the vortex lattice in 2H-$NbSe_2$.

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for which $I(\rho) = 0.36 (I_{max} - I_{min})$ [3]. The dependence of the vortex-core radii on the applied external field is shown in Fig. 2. We found an almost linear decrease of the radii with increasing field for $0 \leq H/H_{c2} \leq 0.3$. The extrapolated core radius for an isolated flux line amounts to about $\rho \approx 3.4\ \xi$, where ξ denotes the zero-temperature Ginzburg-Landau coherence length. All data were obtained at a tunneling voltage of $V_0/V_g = 0.64$.

As a first attempt to theoretically understand the experimental data we calculated self-consistent solutions of the Usadel equations [4] in the Wigner-Seitz cell geometry [5]. The resulting tunneling current profiles at $V_0/V_g = 0.64$ are shown in Fig. 3 for various external magnetic fields. The curves are in qualitative agreement with the experimental line scans. The zero-field vortex radius deduced according to the aforementioned definition amounts to $\rho \approx 5\ \xi$ which is considerably larger than the experimentally obtained value. However, the slope of the $\rho(H/H_{c2})$ curve deduced from Fig. 3 is almost the same as that obtained from Fig. 2.

The discrepancy in the absolute ρ values between experiment and theory is not so surprising since the Usadel framework used for the calculations strictly holds only for the dirty limit. 2H-$NbSe_2$ is, however, a clean superconductor. In particular the assumed dirty-limit-type variation of the pair potential $\Delta(r/\xi)$ broadens the curves in Fig. 3 with respect to clean-limit curves. Other clean-limit features, such as bound vortex states and the zero-bias peak [6], are considered to be less important, since the present observations are based on tunneling-current (rather than differential-conductivity) measurements at relatively high T/T_c. Thus, any subgap fine structure related to the vortices should be thermally smeared out.

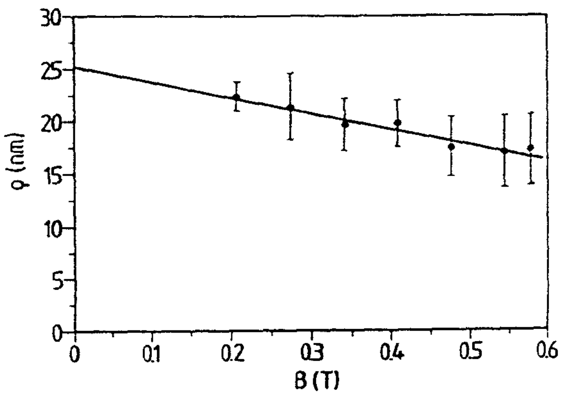

Figure 2. Measured vortex-core radii as a function of externally applied magnetic induction.

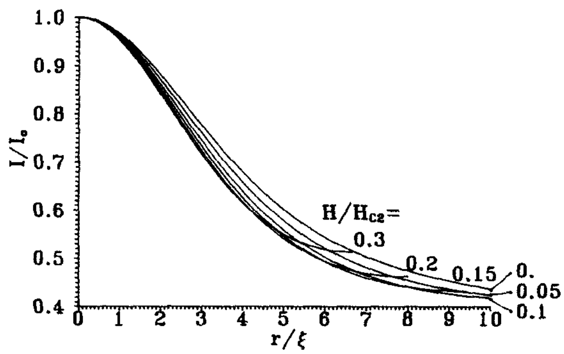

Figure 3. Calculated decay of the tunneling current as a function of separation from the vortex center for various external magnetic fields.

Acknowledgments

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