COMMENTS AND ADDENDA

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Attractive Interaction between Vortices in Nb

D. K. Finnemore, J. R. Clem, and T. F. Stromberg*
Ames Laboratory-United States Atomic Energy Commission and Department of Physics, Iowa State University, Ames, Iowa 50010
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The equilibrium spacing between vortices a_0 at fields just above H_{C1} has been calculated from previousl, published magnetization data for Nb. Results show that a_0 is proportional to $(1-t)^{-1/2}$, where t is the reduced temperature. Hence, the vortex lattice spacing diverges at the critical temperature in the same manner as the penetration depth and the coherence distance. The magnitude of the lattice spacing is about four coherence distances.

Recent experimental results[1-4] and theoretical calculations[1,5] have shown that there may be an attractive interaction between vortices for low-κ long-mean-free-path materials. Studies of the vortex lattice structure by decoration techniques[6] have shown the coexistence of Meissner and Shubnikov (vortex) regions[2] in adjacent portions of the sample in just the manner which would be expected if there were a long-range attraction between vortices. In addition, neutron-diffraction and magnetization measurements[4] have shown that the equilibrium spacing is about 1900 Å for Nb at 4.2 K. Similar values have been obtained for Pb-Tl alloys.[7] We present here an analysis of previously published Nb magnetization data to give the temperature dependence of the vortex spacing.[8]

Figure 1 gives a detailed description of the magnetization data in the region of H_{C1}. There is a rapid drop in the magnetization when flux first enters the sample and then a sharp change in slope at H_k. The slope of the magnetization curve between H_a and H_k (see Fig. 1), although very steep, is still smaller than would be expected from simple geometrical considerations for these samples. This might be caused by the fact that the crystalline axis is not aligned with the cylindrical axis of the specimen. If the vortices do not align with the applied field but rather with the crystalline axis as shown by neutron diffraction,[4] then distorted magnetic field patterns would result and the effective

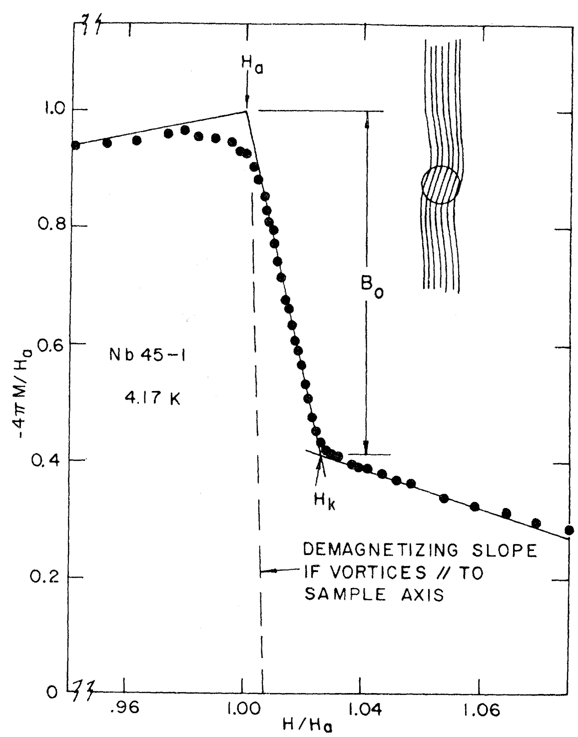

FIG. 1. Magnetization curves in the region of H_{C1}. The effective demagnetizing factor for this sample may be larger than the geometrical factor because the vortices align with the crystalline [110] axis rather than with the applied field.

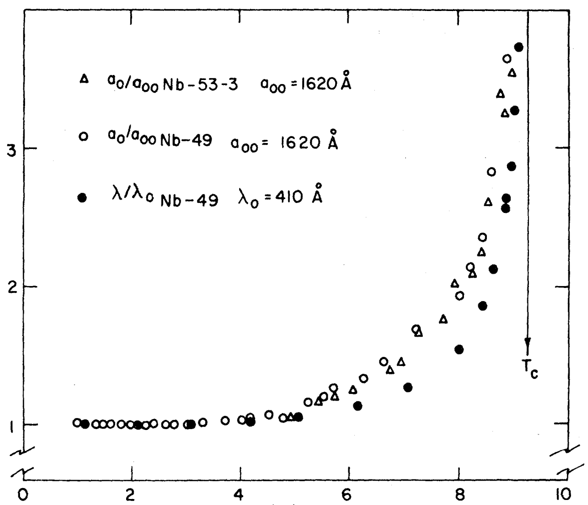

FIG. 2. Spacing of quantized vortices in Nb.

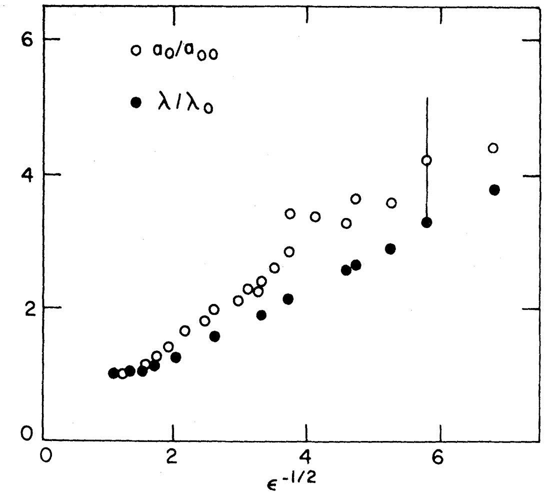

FIG. 3. Comparison of the temperature dependence of the vortex spacing at H_{C1} with the penetration depth. Both diverge as $\epsilon^{-1/2} = (1-t)^{-1/2}$.

demagnetizing factor would be much larger. The inset of Fig. 1 illustrates the manner in which this anisotropy might distort the field pattern for a spherical sample. The magnitude of the drop in induction, marked B_0, is about 55% of H_{C1} for all temperatures below 9.0 K. In addition, the width of the sharp drop region $(H_k - H_a)/H_k$ is nearly constant at slightly over 2% at all temperatures. If we use the Seeger[1,3,4] interpretation of the rapid drop in magnetization to calculate the vortex lattice spacing according to the formula $a_0 = (2\varphi_0/\sqrt{3}\,B_0)^{1/2}$, then the results shown in Fig. 2 are derived. At low temperatures a_0 approaches 1620 Å in fair agreement with the neutron-diffraction result of 1900 Å. As the temperature increases toward the transition temperature, the value of a_0 diverges in a manner similar to the divergence of the penetration depth.[9] This is shown explicitly in Fig. 3, where both a_0 and λ are plotted against the divergence parameter $\epsilon = (1 - t)^{-1/2}$, which is expected for λ from the Ginsburg-Landau theory.[10] Both a_0 and λ are normalized by their value at $t = 0$. The scatter in the data arises primarily because there were slight changes in temperature (~0.0001 K) during the half-hour ordinarily required for the measurement. Unfortunately, the errors in the data are too large to determine whether a_0 diverges at some temperature less than T_c. All that can be said is that the divergence temperature is greater than 9.0 K.

For these Nb samples[8] $\xi_0 = 430$ Å, $\lambda = 400$ Å, the London penetration depth $\lambda_L = 350$ Å, and the mean free path is on the order of 5000–10 000 Å. Hence the picture which emerges from these data is an array of vortices with a radius of about 400 Å separated on a lattice network with a spacing of about 1600 Å. As the temperature approaches T_c, all three parameters a_0, λ, and ξ approach infinity as $(1-t)^{-1/2}$.

*Present address: Department of Physics, New Mexico State University, Las Cruces, N. M. 88001.

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