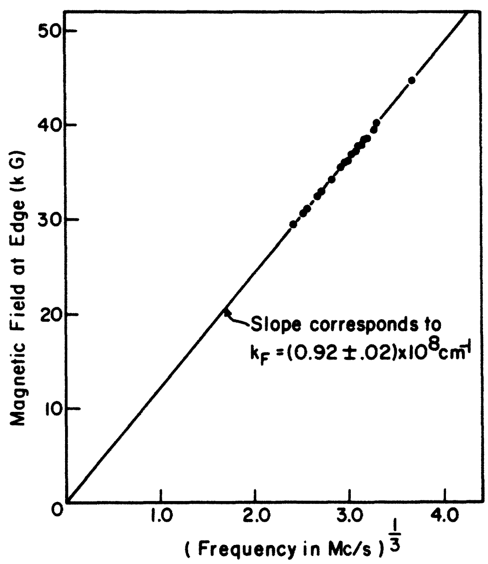

FIG. 3. Plot of the value of the magnetic field at the edge against the cube root of the frequency. Measurements were made at 18 frequencies between 14 and 50 Mc/sec.

with the theoretical value of 0.93×10^8 cm^{-1} obtained assuming one electron per atom and the lattice constant of 4.225 Å.[10] The principal error in k_F comes from the lack of precision in the calibration of the superconducting magnet, so the above accuracy can be improved.

To summarize, cyclotron resonance has been performed using helicon waves with frequencies ~10 000 times smaller than the electron cyclotron frequency and the experimental technique used promises to lead to accurate measurements of the curvature at points on the Fermi surface.

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SURFACE BARRIER IN TYPE-II SUPERCONDUCTORS*

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Bean and Livingston[1] have recently predicted the existence of an image-effect surface barrier to the penetration of magnetic flux into a type-II superconductor. We report here the experimental observation of a greatly enhanced superconducting to mixed-state transition field in some regions of an electropolished specimen of $Nb_{0.993}O_{0.007}$ and in another of $Nb_{0.33}Ta_{0.67}$. Our observations are consistent with the predictions of the Bean-Livingston theory that a plane surface on a type-II superconductor will produce a nucleation barrier that will increase the initial flux penetration field to near the thermodynamic critical field H_c, and that roughening the surface will permit flux penetration near the superconducting to mixed-state transition field H_{c1}. They are also shown to be inconsistent with the most plausible alternative explanation that electropolishing may have produced a chemically or structurally altered surface sheath. Joseph and Tomasch have also recently found experimental evidence for the existence of the surface barrier by a different technique than ours.[2]

The preparation of the $Nb_{0.993}O_{0.007}$ wire[3] specimen has been described earlier.[4] The $Nb_{0.33}Ta_{0.67}$ specimen was sectioned from a 0.76-mm wire annealed 291 hours at 1650°C and 10^{-7} mm Hg. Electropolishing was carried out in an acid mixture of two parts H_2SO_4 to one part HF. Several minutes near 10 V were followed by several minutes near 3 V. The voltage measurements were between the specimen and a platinized platinum cathode.

Since the existence of localized imperfections, for example at grain boundaries, is to be expected even along the lengths of electropolished specimens, we have probed the specimens by applying localized pulsed magnetic fields along their lengths. The specimens were tested at 4.2°K in one of a matched pair of field and pickup coil units connected in series. With the specimen either withdrawn or normal the dB/dt voltages from the two pickup coils canceled each other during a field pulse. The specimen unit consisted of 29 pickup turns of 50-μ wire wound on a 1.24-mm quartz capillary for an axial length of 1.25 mm, and of 90 field-coil turns wound over the pickup coil to an outside diameter of 2.14 mm. The section of the specimen at the field coil was varied by means of a draw-thread leading out of the top of the Dewar.

The field at the surface of the superconducting specimen is the sum of the applied field and that produced by induced surface currents. This total is best determined experimentally by adding a known biasing field and measuring the change in the field-trace voltage needed to rematch that trace with a fiducial break in the dM/dt trace. The field varies from 580 to 660 Oe/A, with a probable error of about 3%, for specimens from 0.30 to 0.65 mm in diameter.

Figure 1 shows two sets of oscilloscope traces of pickup-coil voltage and applied magnetic field versus time for the $Nb_{0.993}O_{0.007}$ specimen. The field trace is of the voltage over a resistance in series with the field coil. Trace A is for the specimen in an optimum position. (The trace bottoms near -18 mV.) For trace B the specimen was moved 1.4 mm upward. The trace of dM/dt is proportional to dH/dt as long as no flux penetrates into the specimen. For trace A this

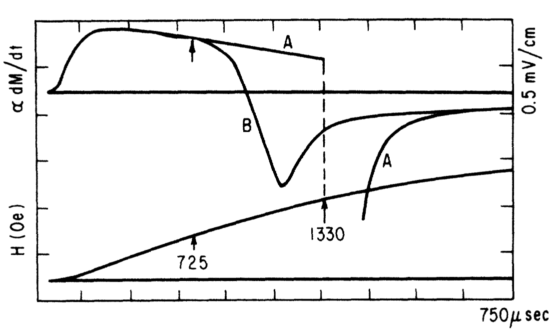

FIG. 1. Oscilloscope traces showing initial penetration of flux into an electropolished $Nb_{0.993}O_{0.007}$ wire at a field of 1330 Oe with the field coil at an optimum position, and at 725 Oe with it 1.4 mm away (H_{c1} = 580 Oe).

condition holds to a field H_s of 1330 Oe, while for trace B the main penetration starts near 725 Oe. In most traces other than type A a slight flux penetration is detectable before the main penetration, at a field near H_{c1}.

Conventional tests in an electromagnet on an adjacent section of wire and, earlier, on a similarly prepared specimen[5] give a superconducting to mixed-state transition field H_{c1} of 580 Oe, a thermodynamic critical field H_c of 1360 Oe, an upper limit H_{c2} for the mixed state of 7000 Oe, and a critical temperature T_c of 8.8°K. Thus the penetration field H_s experimentally observed here is more than twice H_{c1} and is approximately equal to H_c. In other tests on this specimen penetration fields up to 1500 Oe (10% above H_c) have been observed. It is not yet clear what the theoretical limit for H_s should be. In their Letter,[1] Bean and Livingston made a rough estimate of $H_c/\sqrt{2}$ for a material with the penetration depth much greater than the coherence length. κ, a measure of their ratio, equals 4.0 for $Nb_{0.993}O_{0.007}$.

Figure 2 shows the penetration field contour along the length of the $Nb_{0.993}O_{0.007}$ specimen after a particular electropolish. The open circles show regions where flux penetration occured abruptly, as in trace A of Fig. 1. Tests at one of these optimum positions show that the penetration field H_s does not vary with field rise rate (ΔH generally less than 20 Oe) in the observed range of 8×10^4 to 22×10^7 Oe/sec. Thus it is unlikely that dynamic effects account for the high penetration field. Abrupt penetrations also occurred at regions shown by the squares, but they were preceded by gradual penetrations starting at coil-center fields shown by the inverted triangles (∇). One may note that the abrupt penetrations (1270 to 1400 Oe) all occur near the thermodynamic critical field H_c of 1360 Oe. The gradual penetrations (∇) probably arise at weak spots in the fringing field of the coil. The triangles (Δ) and solid circles (●) show regions with traces like B of Fig. 1 and with penetration fields at the local minima and maxima, respectively. These less perfect regions still have penetration fields above H_{c1} (580 Oe). However, gently circumscribing the specimen with a razor blade at two positions reduced the penetration fields there to about 645 and 590 Oe, respectively.

The dashes above the data points show the positions of grain boundaries along the length of the specimen. The abrupt penetrations all fall between these boundaries. Microscopic examination of the specimen under oblique lighting re-

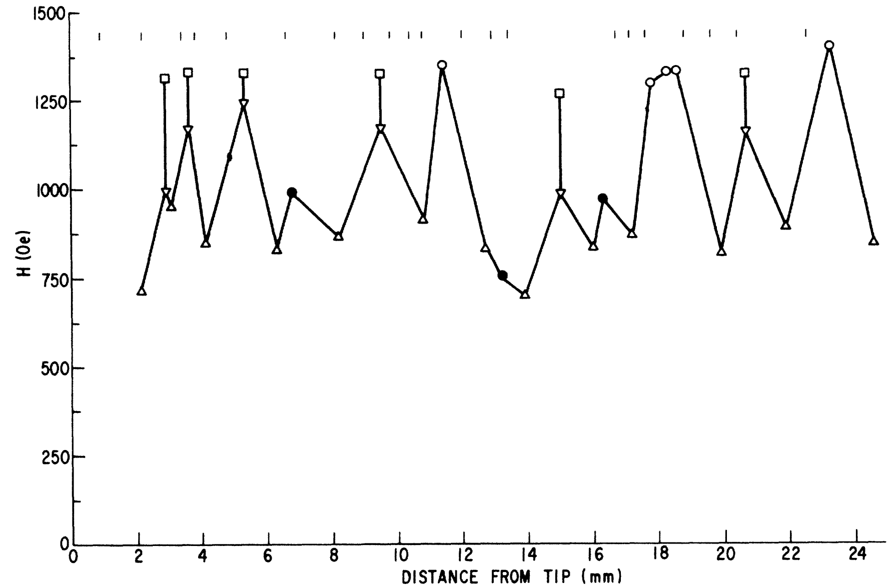

FIG. 2. Maximum (○,□) and minimum (△) initial flux penetration fields along the length of an electropolished $Nb_{0.993}O_{0.007}$ wire. The positions of grain boundaries are indicated by the row of dashes just above the field data. For explanation of other symbols, see text.

vealed minute surface steps at the grain boundaries that would, from the theory, be expected to make flux penetration easier than at a smooth planar surface. However, grain boundaries need not be weak spots. Subsequent tests on another specimen of niobium with probably somewhat less than 0.7 at. % oxygen showed a continuous region of 2.3 cm over which only abrupt penetrations occurred, all at 1560 ± 20 Oe. These results followed a thus far uniquely superior electropolish at 9 V.

Tests on the electropolished specimen of $Nb_{0.33}Ta_{0.67}$ showed a range of penetration fields from 180 to 320 Oe. The specimen was also tested after the surface was roughened with emery paper. The average penetration field then became 175 Oe, with a maximum of 200 Oe. The average before roughening was about 245 Oe, and after the next electropolish, about 235 Oe. Conventional tests on similar material give values of $H_{c1} = 110$ Oe, $H_c = 310$ Oe, $H_{c2} = 1600$ Oe, and $T_c = 5.6\,°K$. Thus the upper penetration field of 320 Oe is about equal to H_c.

Whether flux penetrates abruptly at a high field or gradually at a low field makes no difference in the manner of flux expulsion as the field pulse falls. For all positions along the length of the $Nb_{0.993}O_{0.007}$ specimen it becomes abruptly complete near 650 Oe, independent of the amount of flux that originally entered. This is what one would expect from inspection of the bulk magnetization curve of Fig. 9 of reference 4. If, on the other hand, electropolishing chemically or physically altered the structure of the surface material, one might expect the sheath producing the high penetration field to trap the interior flux near the high field and to prevent the abrupt completion of flux expulsion near the field H_{c1} of the bulk of the specimen.

We wish to thank C. P. Bean and J. D. Livingston for a number of valuable discussions. We are grateful to R. W. Powers for valuable advice on electropolishing. We also wish to thank W. A. Healy for capable help in measuring the conventional properties of the materials tested.

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[5]Figure 9 of reference 4.