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EVIDENCE FOR NORMAL REGIONS AT LOW TEMPERATURES IN THE SUPERCONDUCTING MIXED STATE

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The microwave surface resistance has been measured for a number of type-II superconductors as a function of magnetic field and temperature.[1-3] With such measurements one can determine H_{c1}, H_{c2}, H_{c3}, and several properties of the Bean-Livingston surface barrier[4] with no assumptions as to the absorption mechanism in the mixed state. The model of the mixed state with which we can most naturally explain the absorption has normal regions of finite extent at the centers of the Abrikosov flux tubes. This is at variance with the concept that the material is entirely superconducting except along zero-volume lines. Thermal conductivity experiments,[5] while establishing the validity of an average field-dependent energy gap, do not rule out a model where the flux tubes have finite normal cores. The existing data on specific heat[6,7] can be interpreted to agree with a significant fraction of material being normal. In referring to finite regions about the centers of flux tubes as being "normal," we do not exclude the possibility that the regions do have finite, but negligibly small, energy gaps.[8]

In all of the materials studied (Pb-Tl alloys; In-Bi alloys; Pb-In; Nb; single-phase, highly stoichiometric Nb_3Sn; and single-crystal V_3Si) when κ is not close to $1/\sqrt{2}$, the surface resistance $R(H)$ can be characterized as follows: When $\vec{H}$ is applied perpendicular to the plane of the thin plate sample, the field penetrates at very low values, and $R(H)$ rises approximately linearly to its value in the normal state R_n at H_{c2}. With $\vec{H}$ in the plane of the plate and perpendicular to the microwave current, $R(H)$ does not rise until $H > H_{c1}$ and then rises, also approximately linearly, changing slope at H_{c2}, but not reaching R_n until $H = H_{c3} \simeq 1.7H_{c2}$. When $\vec{H}$ is parallel to microwave current the absorption is much smaller until fields close to H_{c2}. A figure illustrating this behavior is shown in reference 2. The anisotropy for the magnetic field in the plane of the sample surface—defined as the maximum ratio of $R(H)$ for the two orientations—is proportional to κ. At low reduced temperature $R(H/H_{c2}(T))$ is approximately independent of temperature.

We will assume the mechanism for the absorption of microwave energy (photon energy small compared to the energy gap) in the mixed state is essentially the same as in the pure superconducting state, i.e., absorption by quasiparticles (normal electrons in the two-fluid model).[9] We further assume that these normal electrons are so concentrated at the centers of the flux tubes that a region of diameter approximately equal to the coherence length is essentially normal. This results in a fraction $(H - H_{c1})/(H_{c2} - H_{c1}) \simeq H/H_{c2}$ of the material being essentially normal. The reasons for the assumption that the normal electrons are concentrated in essentially normal regions are these: (1) The approximate temperature independence of $R(H/H_{c2}(T))$ as $T \to 0$ indicates that the absorbing normal electrons are not ther-

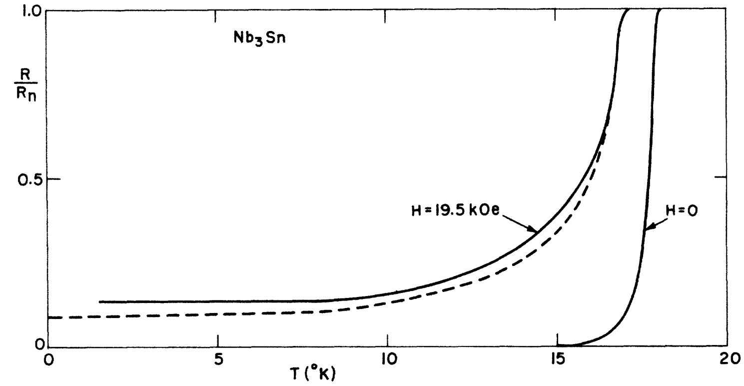

FIG. 1. Real part of the surface impedance of Nb_3Sn at 22 kMc/sec as a function of temperature. The magnetic field $\vec{H}$ is applied parallel to the surface of the sample but perpendicular to the microwave current. The dashed curve is a "theoretical" curve explained in text. It is assumed that on the scale of this figure $R(H=0)=0$ at the lowest temperature of measurement

mally excited in regions of significantly large energy gap Δ. (2) If the absorption were due to normal electrons in superconducting regions, R should vary as the square of the frequency ν. Experimentally, R(22 kMc/sec,H) is very similar to R(55 kMc/sec,H). (3) In an extrinsic local superconductor $R \ll R_n$ if $\nu \ll \Delta$ unless $N_n \gg N_s$, where N_n and N_s are the number of normal and superconducting carriers, respectively. Thus for the Pb-In alloy of Fig. 2, $R(H=\frac{1}{2}H_{c2}) \sim \frac{1}{2}R_n$ can be interpreted to mean that about one half the volume of the material is essentially normal. If one wished to attribute this surface resistance to normal carriers uniformly distributed over the material, the $R(T,H=0)$ curve (and $N_n \propto t^4$) would yield $N_s/N_n = 0.04$ for $H \sim \frac{1}{2}H_{c2}$. The uniform distribution would then give an average order parameter much smaller than that predicted by the Abrikosov theory and found so successful in the analysis of the thermal conductivity.[5]

The anisotropy in $R(H)$ for H in the plane of the sample would be expected from a structure of normal and superconducting regions if the normal regions are thin compared to the microwave penetration depth. When the microwave current is flowing in the direction of H the superconducting regions can "short out" the essentially normal regions. The boundary value problem of a surface with a complex conductivity sinusoidally modulated in one direction (laminae) has been solved and does show an appropriate anisotropy.[10] It is not yet clear whether the solution of the two-

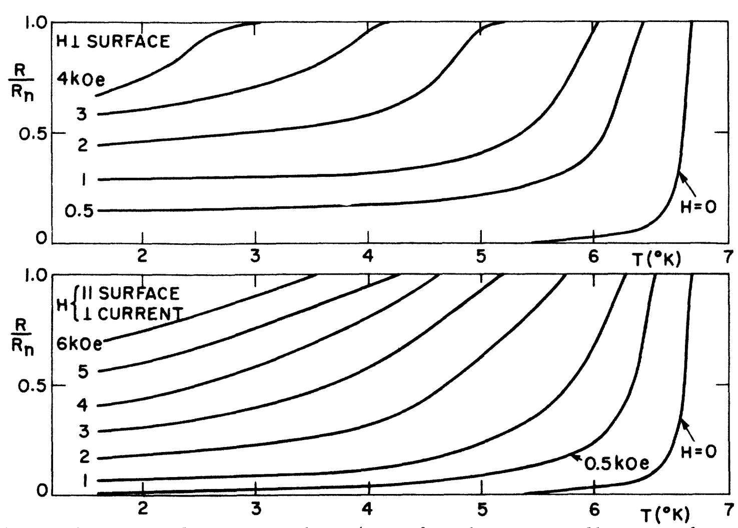

FIG. 2. Real part of the surface impedance at 22 kMc/sec of a $Pb_{0.83}In_{0.17}$ alloy as a function of temperature at various magnetic fields. It is assumed that on the scale of this figure $R(H=0)=0$ at the lowest temperature of measurement.

dimensional problem can yield anisotropies as large as have been observed experimentally.

In Fig. 1 we plot (full curves) R vs T for a sample of single-phase, highly stoichiometric Nb_3Sn of particularly low residual resistivity (1×10^{-5} Ω-cm). The magnetic field ($H=19.5$ kOe) is applied parallel to the sample surface and perpendicular to the microwave current. In Nb_3Sn we do not observe surface superconductivity above H_{c2}. In this material the penetration depth is large compared to the coherence length and the microwaves largely penetrate any superconducting surface. Also, measurements above H_{c2} could only be made at high reduced temperatures where the order parameter of any superconducting surface would be small.

The dashed line represents $R/R_n = 19.5$ kOe/$H_{c2}(T)$, where the critical temperature at 19.5 kOe and the Gor'kov temperature dependence have been used to determine $H_{c2}(T)$. It is seen that there is no reduction of the absorption with temperature at low temperatures, and, indeed, most of the temperature dependence at higher temperatures is explained by that of $H_{c2}(T)$. No attempt has been made to add the loss due to the thermally excited normal electrons (as evidenced in the curve for $H=0$) into the "theoretical" curve.

More complete data could be taken on a Pb-In alloy since H_{c2} was attainable at all temperatures. It is seen in Fig. 2 that the absorption is always greater when H is perpendicular to the surface. Only in this case do the flux tubes penetrate the surface leaving the essentially normal centers completely unshielded.

Hake and Brammer[6] have made accurate measurements of the specific heat of a V + 5 at.% Ta alloy and show that the data at temperatures $T \ll T_s(H)$ [$T_s(H)$ is the critical temperature in a field H] can be fitted with the expression

$$C_{es}(H,T) = a(H)\gamma T_s(H)\exp[-b(H)T_s(H)/T], \qquad (1)$$

where a and b are adjustable parameters and γ the electronic specific-heat coefficient. The data can also be fitted with the following equation, which assumes the existence of essentially normal regions occupying a fraction of the material $H/H_{c2}(T)$:

$$C_{es}(H,T) = a'(H)\gamma T_s(H)\exp\left[-\frac{b'(H)T_s(H)}{T}\right]\left(1-\frac{H}{H_{cz}}\right) + \gamma T\frac{H}{H_{cz}}\left(1-\frac{T}{H_{cz}}\frac{dH_{cz}}{dT}\right). \qquad (2)$$

Hake has calculated the entropy of the superconducting phase at T_s using Eq. (1) for the low-temperature region and obtained an 8% difference between the normal and superconducting phase at 4 kOe. Using Eq. (2) we obtain only a 2% difference. If the transition at H_{c2} is second order, the actual entropy difference must be zero.

Since this work was done a preprint by Caroli, deGennes, and Matricon[8] has come to our attention. In this work a closely spaced spectrum of excitations filling the energy gap in the region within a coherence distance of the flux-tube axis is predicted. This would render this region essentially normal at temperatures higher than a few millidegrees.

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[9]An absorption mechanism involving the vibration of flux tubes has been discussed for lower frequencies [P. G. deGennes and J. Matricon, Rev. Mod. Phys. 36, 45 (1964)]. The similarity of our results for strongly pinned flux tubes (Nb_3Sn) and weakly pinned flux tubes (Pb-In), and a lack of frequency dependence, lead us to believe that this is not the major absorption mechanism at microwave frequencies. A very broad structure observed at relatively low fields may be due to flux tube vibration.

[10]G. Fischer, to be published.