not change, we get $\alpha \approx 0.43$. (Our calculations are rather rough and the obtained values for α should be regarded as giving an indication about the order of magnitude only.)

On the other hand, it is known that the phonon mechanism, when acting in a region of rapidly varying density of states (like the f bands)[1,5] can lead to a large positive value of α.[6] Whether or not the phonons are the only attractive mechanism involved in α uranium, it is clear that they must play an important dynamic role, rather than the passive role of spoiling the polarization attraction, if in fact the latter exists. There is compelling evidence that the corresponding electronic core-polarization effects do not enter d-band superconductors.[7] Further investigations of α uranium may show the same to be the case there.

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EXPERIMENTAL OBSERVATION OF DEPAIRING PHENOMENON IN SUPERCONDUCTING TIN FILMS[*]

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The gradual decrease to zero of supercurrent due to depairing in thin tin films has been observed as a function of external magnetic field in reasonable agreement with theory.

The current-carrying state of a superconductor has been discussed theoretically by various investigators.[1-6] They showed that a current in a superconductor provides a mechanism for breaking the pairs and discussed the gradual decrease of the current, after having reached its maximum value, as the pairing momentum is increased beyond the value at which the pairs begin to be energetically unstable with respect to the break up into individual quasiparticle excitations. The theoretical prediction is that for a type-I superconductor, a second-order phase transition to the normal state induced by an external magnetic field, which is not normally seen, should be observable under appropriate conditions. Fulde and Ferrell[4] have discussed in detail what these appropriate conditions are. We wish to report in this paper successful experiments, based on the suggestion of Fulde and Ferrell,[4] in which we have observed the complete depairing regime in thin tin films and the change from first to second order of the superconducting transition induced by an external magnetic field.

When a hollow cylindrical superconducting film, thin compared with a penetration depth, is placed in an external axial magnetic field, the flux φ_S expelled from it is given by the relation

$$\varphi_S = (\varphi_0/\gamma)F(\varphi/\varphi_0), \qquad (1)$$

where $\gamma = \lambda^2 l/\tau\Sigma$, λ is the penetration depth, τ is the film thickness which is assumed to be much smaller than λ and the coherence length, l and Σ are the circulating path and area enclosed by the induced current, respectively, φ is the flux enclosed by the film, and φ_0 is the critical value of the flux necessary for complete depairing of the film. $F(\varphi/\varphi_0)$ is a function of φ/φ_0 which is equal to φ/φ_0 for small values of φ/φ_0 and goes to zero smoothly at $\varphi/\varphi_0 = 1$. Equation (1) does not completely determine the value of φ_S since it also satisfies another equation, namely

$$\varphi_s = \varphi_{ex} - \varphi, \qquad (2)$$

where φ_{ex} is the externally applied flux. The value of φ_s is determined by the simultaneous solution of (1) and (2). It is found that φ_s is a single-valued or multivalued function depending upon the value of γ and $F(\varphi/\varphi_0)$ as discussed in detail by Fulde and Ferrell.[4] Their discussion can be summarized as follows. For such thin samples, a local theory applies and the induced supercurrent $\vec{J}$ which expels the flux is related to the total vector potential $\vec{A}$. The total vector potential $\vec{A}$ has two sources, the external field $\vec{A}_{ex}$ and the self-induced field $\vec{A}_s$, related by

$$\vec{A} = \vec{A}_{ex} - \vec{A}_s. \qquad (3)$$

Because of the diamagnetic property of superconductors the self-induced field $\vec{A}_s$ is opposite in sign to the applied field $\vec{A}_{ex}$. This Eq. (3) is equivalent to (2) since the $\vec{A}$'s are directly related to the flux φ by the relation

$$\oint \vec{A}_i \cdot d\vec{l} = \varphi_i, \qquad (4)$$

where the closed line integral is around the circumference of the sample, and i can be any of the symbols ex, s, or nothing. Both $\vec{A}_s$ and $\vec{A}$ are related to $\vec{J}$; $\vec{A}_s$ has a linear relation proportional to the inductance of the sample, and A has a more complicated relation because of the depairing effects[1-5] as indicated by Eq. (1). What is desired is to verify Eq. (1) which relates φ_s to φ, which from the above discussion is equivalent to a relation between $\vec{J}$ and $\vec{A}$. The experimental complications arise because one cannot apply $\vec{A}$ to the sample directly, but instead applies $\vec{A}_{ex}$. The value of $\vec{A}$ that one obtains is determined by the simultaneous solution of Eqs. (1) and (2). This can be done graphically for a fixed φ_{ex} or $\vec{A}_{ex}$ by plotting φ_s (or $\vec{J}$ which is proportional to it) as given by both Eqs. (1) and (2). The intersection of the two curves determines both A and J. The relation (2) is analogous to a linear load line in electrical circuit theory. In Eq. (1) for the values of φ where depairing becomes a large effect, φ_s <u>decreases</u> with increasing $\vec{A}$. This is analogous to a negative resistance region in electrical circuit theory. Just as in electrical circuit theory, the depairing region (the "negative resistance region") can be measured only if the slope of the load line is greater than the slope of the depairing region so that there is only one intersection (a good load-line condition). If there are two intersections as would be the case for a small-sloped load line, then only the intersection corresponding to the smaller φ (or $\vec{A}$) value would be measureable (a bad load-line condition). As $\vec{A}_{ex}$ is increased for the bad load line, a maximum value of $\vec{A}$ is reached for which $\vec{J}$ is still finite and beyond which there are no further interactions. At this point the sample switches discontinuously along the load line to $\vec{J}=0$, i.e., to the normal state, the usually observed first-order transition. In the good load-line condition the complete curve of (1) is followed and the second-order transition to the normal state should be observable. A good load line can be attained by experimentally setting γ large enough which corresponds to a small sample inductance. The parameters l, τ, and Σ can be set in making a sample such that the temperature variation of λ produces a good load line near the transition temperature permitting the observation of the second-order transition and a bad load line at lower temperatures which then shows the usual first-order transition. In the experiment reported here, these conditions are met where γ varied from 4 to 0.95.

The depairing regime is observed experimentally by measuring the supercurrent in a thin tin film induced by an external magnetic field. The thin tin film forms a part of a multiply connected, sandwich-type, superconducting sample shown schematically in Fig. 1. The sample is prepared by high-vacuum deposition of films of lead (thickness $d_1 \gg \lambda_{Pb}$, the penetration depth of Pb), magnesium fluoride (thickness b) as insulator, and tin (thickness $\tau \ll \lambda_{Sn}$), respectively, on a substrate of pinhole-free, 10^{-4}-in. thick gold foil approximately 1 cm long and 2 mm wide on which a film of magnesium fluoride has previously been deposited to eliminate proximity effects in the sample. A thick film of lead (thickness $d_2 \gg \lambda_{Pb}$) is deposited at each end of the tin film leaving the central portion of the tin film uncovered. These latter lead films act as guard rings to maintain a uniform current density throughout the whole length of the exposed tin film. The gold foil is fixed at one end while the other portion with the sample is free to vibrate. When the superconducting sample is placed in an external static magnetic field directed along the axis of the sample, the amount of the expelled flux in the composite sample varies along its length because of the different thicknesses of the tin and lead films. The change in the expelled flux at the junction of the tin and lead guard films is directly measured in the experiment by its interac-

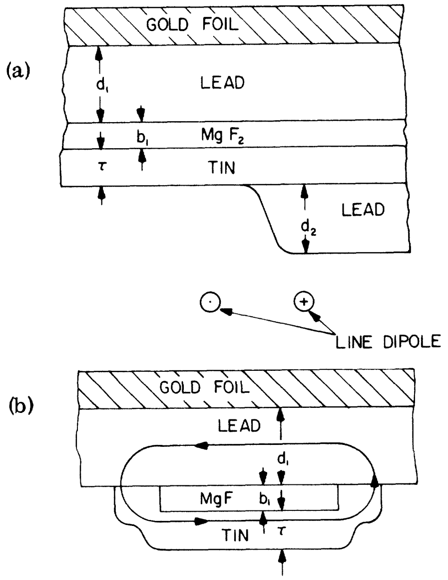

FIG. 1. (a) A schematic of the right-half cross section through the length of the sample. The line dipole is made of two copper wires running parallel to each other and the width of the sample and perpendicular to the plane of the paper. d_1, b, τ, and d_2 are the film thickness of base film of lead, insulating layer of MgF_2, tin, and guard film of lead, respectively. (b) A schematic of a cross section through the center of the sample perpendicular to its axis. This cross section is perpendicular to the one in (a) and indicates the supercurrent path by the loop with the arrow heads. The lead guard films do not show in this cross section since they are present only at the ends.

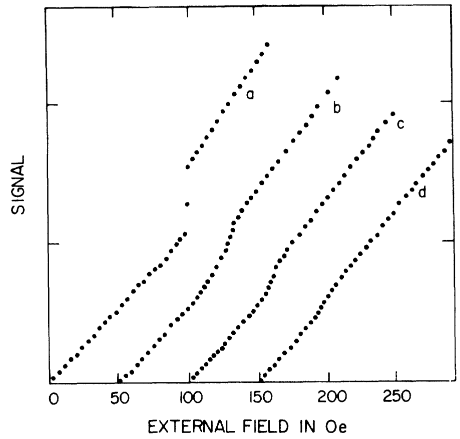

FIG. 2. Measured signal versus magnetic field at (a) 1.96°K, (b) 2.81°K, (c) 3.04°K, and (d) 3.28°K. The curves are each displaced 50 Oe along the horizontal axis from the previous one. The transition temperature T_C for the sample is 3.80°K.

tion with a magnetic line dipole through which is flowing an alternating current at the natural resonance frequency of the foil. This line dipole probes only a few thousandths of an inch on either side of the junction and produces an amplitude of vibration of the sample directly proportional to the change of expelled flux near the junction. The amplitude of vibration is detected by measuring the induced capacitance change between the foil and a fixed reference. The details of the measuring apparatus will be presented in a later publication.

The experimental data of the measured amplitude versus applied field is shown in Fig. 2 for a sample with the thicknesses of the constituent films of $d_1 = 3067 \pm 60$ Å for the base film of lead, $b = 2164 \pm 40$ Å for the magnesium fluoride film, $\tau = 574 \pm 20$ Å for the tin film, and $d_2 = 1982 \pm 40$ Å for the lead guard films. The measurements were taken at 1.96, 2.81, 3.04, and 3.28°K on a sample with a transition temperature T_C of 3.80 °K. The data clearly indicate that at 2.81, 3.04, and 3.28°K the difference in the expelled flux between the tin and lead films initially increases linearly with the applied field until the nonlinear region is reached where the expelled flux from the tin film decreases smoothly to zero with increasing field. At 1.96°K the decrease to zero is abrupt. At higher fields the signal is entirely due to the expelled flux from the lead films as can be verified by measurements above the critical temperature of tin. Before one can conclude that the data indicate a second-order transition due to the depairing mechanism, one must eliminate another possibility as the cause of the gradual transition, namely, different regions of the tin film becoming normal at different fields. Under the right condition this latter could also simulate a gradual transition even though each region of the tin had a first-order transition. This latter possibility was checked by using various driving line dipoles which probed different-sized regions of the tin film in the vicinity of the junction. The shape of the nonlinear region remained the same for all driving dipoles. One would expect that if different regions were transforming at different fields, the driver which probed the smallest region would observe the sharpest transition. Such was not the case. Perhaps the strongest evidence that a second-order transition was being observed is the measured change from a second-order transition at higher temperatures to a first-order transition at 1.96 °K, just as expected by load-line considerations. The observation of a sharp transition at 1.96°K verifies that the tin is all transforming at the

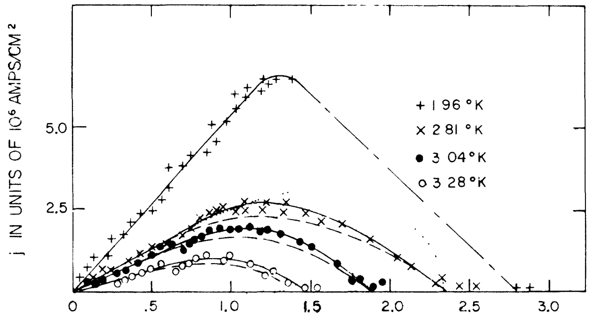

FIG. 3. Depairing curves at 1.96, 2.81, 3.04, and 3.28°K. Dash line curves are as predicted by the Ginzburg-Landau theory or the Maki theory near T_C. The dotted curve is the Maki theory at 0°K. The dot-dashed curve represents the first-order transition.

same critical field within a few gauss. Further studies revealed that the width of the sharp transition was mainly produced by the magnetic field of the line-dipole driver. Decreasing the driver's field sharpened up the transition.

Analyzing the experimental curves of Fig. 2, we obtain the curves in Fig. 3 of current density j versus vector potential A inside the thin tin films. The curves at 3.28, 3.04, and 2.81°K clearly show the depairing regime, where j is not linear with A, and the second-order transition. The curve at 1.96°K shows a small nonlinear region near the maximum but because of the bad load line, the rest of the nonlinear region is not observable, and instead, a first-order transition occurs as shown by the dot-dashed line. Both the magnitude of the maximum current density j_m and the critical vector potential A_c where depairing is complete are of the right order of magnitude to agree with theory. The shape of the curves agrees reasonably well with the Maki theory and the Ginzburg-Landau[7] theory, which the Maki theory reduces to near T_c, as shown by the dashed curves in Fig. 3. For comparison, Maki's calculated curve at 0°K is also shown in Fig. 3. The theoretical curves are normalized to have the same initial slope and A_c as the experimental curves. The experimental curves appear to retain their linearity to higher fields than the theory predicts, i.e., the depairing appears to occur more sharply than predicted by theory. The predicted temperature variation of $A_c \equiv (1-t^2) \times (1-t)^{-1/2}$ for t near 1, where $t = T/T_c$, is just possibly in agreement with the measurements if the experimental uncertainties are included. However, the predicted temperature variation of $j_m \equiv (1-t^2)(1-t)^{1/2}$ fits well with the measurements. A later publication is in preparation which discusses the measurements in greater detail.

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