deviation of the data from the straight-line fit is 0.12 μv/kgauss or an average of 2.4%. To within our experimental accuracy of a few percent then, we find

$$p = +1.$$

If we assume that our measured potentials arise from changes in the Fermi level of the bulk mateial and are not complicated by contributions from electron surface states,[1] then it is possible to draw some qualitative conclusions about the d-band structure of iron. Such conclusions are, of course, subject to the qualifications inherent to any description which neglects exchange, spin-orbit effects, etc.

From its definition we see that p may take on all values from -1 to +1 and is a measure of the relative preponderance of states of one spin or the other at the Fermi surface. The value +1 which we find in iron means that $g^-(\epsilon_F)$ is very small, or essentially zero, which implies one of three possibilities:

(a) The spin (-) band lies entirely above the Fermi surface.

(b) The spin (-) band lies entirely below the Fermi surface.

(c) The spin (-) band is split into sub-bands lying both above and below the Fermi surface.

Alternatives (a) and (b) are ruled out since they cannot give a proper accounting of the magnetization and the number of d electrons in iron. Our result, therefore, implies that in iron the states of spin opposed to the magnetization are split into sub-bands lying wholly above and below the Fermi surface. This is consistent with a proposal due to Goodenough[2] employing a phenomenological spectrum of states featuring some localized discrete levels together with bonding and antibonding bands of various spins, widths, and energies. In any case, it becomes clear that spin considerations cannot reasonably be treated as an afterthought in a conventional band-type calculation.

It is interesting to note that in the general case of a ferromagnetic metal a measurement of this shift together with a measurement of the electronic specific heat at low temperatures provides an absolute determination of $g^+(\epsilon_F)$ and $g^-(\epsilon_F)$ separately, since the latter measures $g^+(\epsilon_F)+g^-(\epsilon_F)$ directly.

The author wishes to express his great appreciation to Dr. Henry Belson of the Sperry Rand Corporation for arranging for the evaporation of the iron film.

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[1] C. Herring (private communication). Herring points out that such states could conceivably contribute to our measured potential differences.

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TRAPPED FLUX AND CRITICAL CURRENTS IN SUPERCONDUCTING THIN-FILM RINGS*

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Critical persistent currents have been measured in thin-film tin rings by a mechanical method which utilizes the magnetic moment due to trapped flux in such rings. In addition, this technique yields a measurement of the penetration depth for critical persistent currents in thin films. Currents slightly less than critical have been shown to be truly persistent for periods of more than 10 hours in films whose thickness is less than 5% of the penetration depth. It is found that for tin films less than 700 Å thick, current densities greater than 10^6 amp/cm^2 can be readily achieved within a degree of the transition temperature.

For a cylindrical bulk ring, much thicker than the penetration depth, Silsbee's hypothesis implies the relation $I_c = KaH_c$ for the critical current I_c, where a is the length of the cylinder and K is a numerical constant. This constant (K) was experimentally determined to be 0.8 for the bulk ring used in the present measurements. Near the transition temperature (T_c) the critical current in bulk rings will therefore vary linearly with $\Delta T \equiv (T_c - T)$. In thin-film rings for which the thickness (δ) is very much less than the penetration depth (λ) the kinetic energy of the electrons, rather than the magnetic energy of the excluded field, dominates the free energy, and leads to the relation[1] $I_c = aH_c(8/27)^{1/2}(\delta/\lambda)$. Near T_c this relation gives critical currents proportional to $(\Delta T)^{3/2}$, the same functional dependence predicted by both the BCS[2] and Ginzburg-Landau[1,3] theories for thin films in this temperature range. If the field energy $\frac{1}{2}LI^2$ is effective in determining the critical current, it will dominate the behavior of these thin-film rings and lead to a critical current $I_c = (\sqrt{5})H_c a\,(\delta/r)^{1/2}$ for a ring of radius r.

In these experiments a strip of tin 0.9 mm wide was evaporated uniformly onto a rotating 1-cm-diameter quartz tube maintained at liquid nitrogen temperature. The resulting ring was annealed at room temperature and then suspended in the helium Dewar by a quartz torsion fiber of about 5μ diameter (Fig. 1). A magnetic field of a few gauss was applied perpendicular to the plane of the ring and the ring then cooled to a temperature well below the superconducting transition. This magnetic field was then removed, leaving a trapped flux supported by the critical current at that temperature. The magnetic moment and thus the current due to the trapped flux were determined by measuring the deflecting torque on the ring in a known small field of the order of 0.1 gauss. This measuring field was applied in a direction perpendicular to the magnetic moment of the ring in its zero-field equilibrium position. The ring was then permitted to warm up very slowly (one millidegree per minute) toward T_c, the deflection in the measuring field decreasing smoothly with increasing temperature. Helmholtz coils were used to compensate for the earth's field during the entire experiment. Residual fields were always less than 5 milligauss. The film thickness was determined by weighing a sample film evaporated at the same time as the ring, and the values obtained by this method were consistent with electrical resistivity measurements.

Critical persistent current vs ΔT for two of the thin films and a bulk ring is shown in Fig. 2. In the bulk ring the critical persistent current is linear in ΔT over a fairly large range, becoming parabolic at lower temperatures as expected. When plotted on an expanded scale, it is seen that very near T_c ($\Delta T < 0.01$°K) the critical current deviates from linearity probably due to the expected change from nonlocal to local behavior as λ increases with temperature and here becomes larger than the coherence length (ξ_0). The conditions for applicability of the Ginzburg-Landau theory are thus satisfied, giving $I_c \propto (\Delta T)^{3/2}$ in

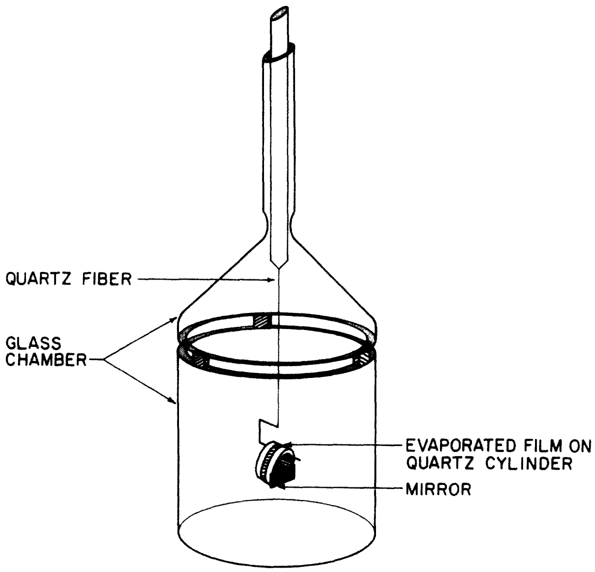

FIG. 1. The apparatus is immersed in a liquid helium bath. Circulating persistent currents are obtained from a simple torque measurement on the suspended ring.

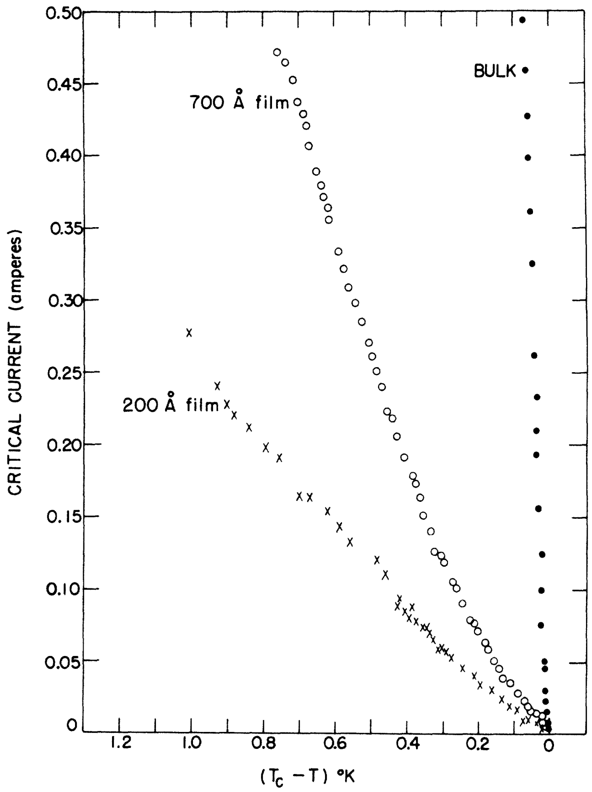

FIG. 2. Variation of critical persistent current with $\Delta T \equiv (T_c - T)$ for the bulk ring and two film samples. These cylindrical rings are 1 cm in diameter and 0.9 mm long.

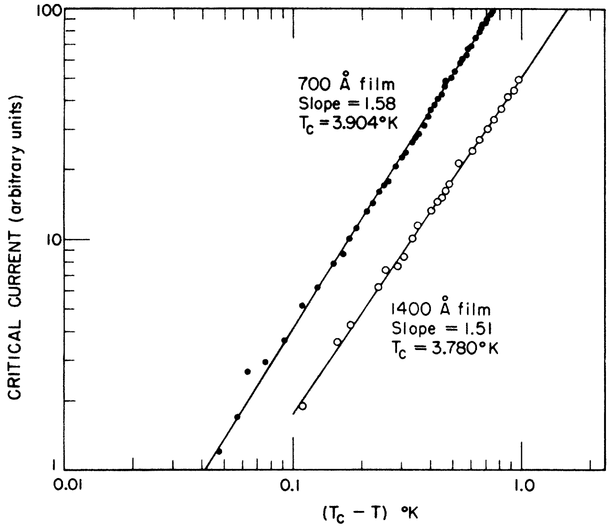

FIG. 3. Log-log plot of the temperature variation of the critical persistent current, showing rather good agreement with the predicted relation $I_c \propto (\Delta T)^{3/2}$.

Table I. Ratio of the penetration depth (λ) to film thickness (δ) for critical persistent currents in thin-film tin rings at various temperatures.

$\Delta T = (T_c - T)$	λ/δ(200 Å)	λ/δ(700 Å)
0.1	36	21
0.2	33	16
0.3	29	15
0.4	27	13
0.5	25	11
0.6	23	10
0.7	23	9

fair agreement with the experimental results.

The critical current (I_c) for the thin-film rings of 1400Å and 700Å thickness is found to be nearly proportional to $(\Delta T)^{3/2}$ down to $\Delta \simeq 0.9$°K as shown in a log-log plot (Fig. 3). This observed temperature dependence precludes the influence of the field energy $\frac{1}{2}LI^2$ on the critical persistent current, since the relation $I_c = (\sqrt{5})aH_c(\delta/r)^{1/2}$ noted above implies a linear dependence of I_c on ΔT which has not been observed. In the case of the 200Å film, the best fit on a log-log plot gives an exponent of 1.35 rather than 1.5, indicating that perhaps for such thin films the temperature dependence of the size of the "flux quanta"[4] is beginning to affect the results. For thicker films, however, changes in ring geometry do not change the temperature dependence of the critical current. A variation of critical current with $(\Delta T)^{3/2}$ for films thicker than 600 Å has previously been observed by Ginzburg and Shalnikov.[5] In their experiment current was passed longitudinally down a long thin-film cylinder and the current needed to destroy the superconducting state was measured directly. Due to difficulties with Joule heating in the normal state, consistent measurements were limited to values of $\Delta \leq 0.2$°K.

On the basis of the simple analysis discussed above, the ratio (λ/δ) is easily obtained from the data on the films and on the bulk ring. A series of these values is given in Table I. The penetration depth for critical persistent currents determined in this way exhibits the usual increase as the transition temperature is approached. For the thicker films confirmation of the relation $\lambda = \lambda_0[1 - (T/T_c)^4]^{-1/2}$ is implicit in the observed temperature dependence of the critical currents. The values of λ obtained from the λ/δ ratios in Table I are roughly 4 times larger than those predicted[6] for thin films. The largest current densities observed in the 200Å and 700Å films were 1.53×10^6 amp/cm^2 and 1.06×10^6 amp/cm^2, respectively; still higher current densities are to be anticipated at lower temperatures. The average flow velocity of the electrons comprising the critical current can be written as $v_c = (e/m)B_c\lambda$. Using (e/m) for free electrons[7] and experimentally determined values for $(B_c\lambda)$, this expression yields values of v_c as large as 10^5 cm/sec, nearly the velocity of sound in tin.

Persistence of the supercurrents was investigated in the 700Å film by maintaining the temperature constant for a period somewhat more than 10 hours during which time no measurable decay in the current was observed. The normal-state time constant for this ring was approximately 10^{-9} sec. No fundamentally different behavior was observed for the persistence of the supercurrent in the 200Å film. Despite the complete penetration of the superconductor by the magnetic field, the trapped flux did not leak out at an appreciable rate. These measurements are being continued and the temperature dependence of the "flux quanta" will be investigated by extending this method to considerably thinner films.

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QUANTUM INTERACTION OF MICROWAVE RADIATION WITH TUNNELING BETWEEN SUPERCONDUCTORS

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Electron tunneling has been used[1-4] to determine the width of the energy gap in the quasi-particle excitation spectrum of superconductors. The experiment is usually carried out using two metal films separated by a thin oxide layer. A good quantitative agreement between theory and experiment was obtained[1-4] by assuming that the matrix element of the transition of an electron from one side of the barrier to the other can be treated as a constant over the energy range of interest. A discussion of tunneling from a many-particle point of view was given by Bardeen[5] to show the plausibility of this assumption. Bardeen[5] further shows that coherence factors in superconductivity do not influence the tunneling process, since the matrix element depends only on the tail of the electron wave function in the barrier region where it is essentially the same as in the normal state. Thus the only relevant factor is the density of states in energy and the net tunneling current may be expressed by an integral over the energy E of the form[2,3]

$$I(V) = \text{const} \times \int \rho_1(E)\rho_2(E+eV)[f(E)-f(E+eV)]dE, \quad (1)$$

where ρ is the density of states, f the Fermi function, and V the applied voltage.

Tien[6] suggested the use of optical excitation of electrons across the energy gap of the superconductor to modify the negative-resistance region in the I-V curve. Burstein et al.[7] discussed the use of tunneling between two superconducting films for the quantum detection of microwave and submillimeter wave radiation. If the microwave frequency ν is such that $h\nu > 2\epsilon_1$, an electron in metal 1 may be excited across the gap and subsequently tunnel through the barrier into an empty state in metal 2. This is shown schematically in Fig. 1(a). If this were the only possible interaction with the electromagnetic field, no change in the tunneling current would be observed for $h\nu < 2\epsilon_1$. We have noticed experimentally, however, that considerable interaction with the microwave field occurs for $h\nu < 2\epsilon_1$. The experimental results suggest that with a bias voltage which brings the top of the filled band on one side of the barrier to a level lower by an amount $h\nu$ from the bottom of the empty band on the other side, an electron may absorb a photon and tunnel from one side to the other as shown in Fig. 1(b). This process seems consistent with tunneling from a many-particle point of view. Absorption by a tunneling electron of more than one photon has also been observed.

We carried out the experiments at different microwave frequencies on samples of Al-Al_2O_3-Pb, In, or Sn. The sample was placed in a resonant cavity with appropriate current and voltage leads connected to the metal films. The results presented consist of oscilloscope traces obtained by

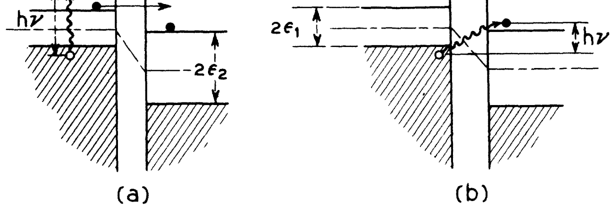

FIG. 1(a). Optical excitation across the gap of metal 1 followed by tunneling through the barrier to metal 2; $h\nu > 2\epsilon_1$. (b) Photon absorption by a tunneling electron; $h\nu < \epsilon_1$.

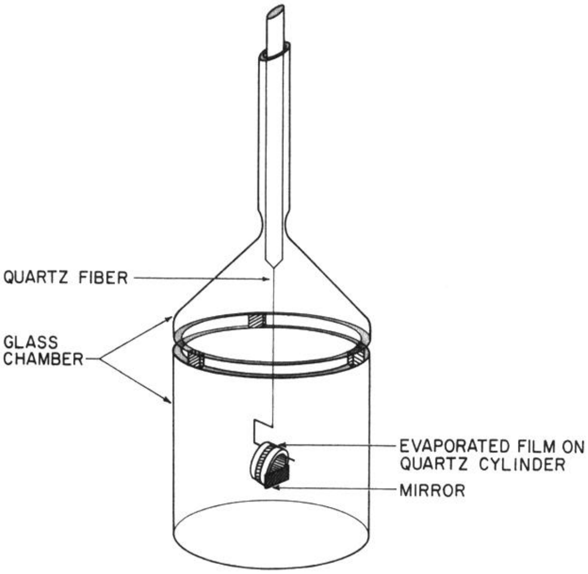

FIG. 1. The apparatus is immersed in a liquid helium bath. Circulating persistent currents are obtained from a simple torque measurement on the suspended ring.