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# A NEW EXPERIMENTAL TECHNIQUE FOR DETERMINING THE BCS INTERACTION PARAMETER IN NORMAL METALS

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# A New Experimental Technique for Determining the BCS Interaction Parameter in Normal Metals

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## ABSTRACT

We have measured the resistance of Pb-Ir-Pb sandwiches in the range 50 mK to 7K. The drop in resistance as the temperature is lowered towards the transition temperature of the Ir is in agreement with the predictions of a simple model involving the BCS parameter (NV). The model suggests that this technique applied to other metals would enable a value of (NV) as low as $10^{-3}$, corresponding to a transition temperature of $10^{-400}$K, to be detected.

The proximity effect[1] between a superconductor (S) and a normal metal (N) has been used in a number of ways to estimate the value of the BCS parameter[2] $(NV)_N$ in the normal metal, and the corresponding transition temperature, $T_{cN}$. This Letter describes a new technique for measuring $(NV)_N$ that involves electric current transport through an SNS junction. We have measured the dependences of the resistance of Pb-Ir-Pb junctions on temperature, current density, and magnetic field, and have qualitatively interpreted them. A simple model of the temperature dependence of the resistance is given that indicates that the method can detect values of $(NV)_N$ as small as $10^{-3}$, corresponding to $T_{cN} \sim 10^{-400}$K.

When a normal metal is in contact with a superconductor, a pair amplitude $(F_N)$ is induced in N. $F_N$ decays approximately exponentially with a decay length[1]

$$k_N^{-1} = \{\hbar v_F \ell / [6\pi k \, (T - T_{cN})]\}^{1/2}, \qquad (1)$$

in the dirty limit, $\ell \ll k_N^{-1}$. If the value of the interaction potential, $V_N$, is exactly zero, the pair potential, $\Delta_N = V_N F_N$, will be zero everywhere in N (see Fig. 1(a)). On the other hand, if $V_N$ is non-zero and positive, $\Delta_N$ will also decay exponentially in N from its value of $\Delta_N^{(i)}$ at the SN interface[1] (see Fig. 1(b)). The experiment described here is a sensitive probe of $\Delta_N$ and hence of $(NV)_N$.

Consider an electric current flowing across the SN interface when $V_N = 0$. An electron in a state $\vec{k}_e$ incident on S from the N-side with an energy $\varepsilon(\vec{k}_e)$ that is less than the value of the pair potential $\Delta_S^{(i)}$ of the superconductor at the interface will be Andreev scattered[3] at the interface. The incident electron couples with one inside the Fermi sea to form a Cooper pair which propagates into S, and a hole excitation with energy $\varepsilon(\vec{k}_e)$ propagates back into N. The conversion from normal current to supercurrent can thus be considered to occur at the SN interface. This result is true at all temperatures such that $\varepsilon(\vec{k}_e) < \Delta_S^{(i)}$ for essentially all incident electrons. Consider next the situation in which $V_N$, and thus $\Delta_N$, are both non-zero, i.e., $0 < T_{cN} < T$. An electron incident from the N-side with $\varepsilon(\vec{k}_e) < \Delta_N^{(i)}$ will encounter an increasing pair potential and be Andreev scattered when $\varepsilon(\vec{k}_e) = \Delta_N$. The conversion from normal current to supercurrent now occurs inside N.

These effects may be investigated by measuring the resistances of SNS sandwiches. Since $F_N$ decays exponentially, in principle there is always an overlap of the pair amplitudes induced into N by the two superconductors, so that a Josephson current can flow.[4,5] In practice, if the N-layer is made sufficiently thick, the two superconductors are decoupled by thermal fluctuations and there is no supercurrent. If $V_N = 0$, we expect the resistance of the sandwich to be equal to the bulk resistance of the N-layer and independent of temperature, provided that $\varepsilon(\vec{k}_e) < \Delta_S^{(i)}$ for most electrons. On the other hand, if $V_N > 0$, we expect the resistance to be less than the bulk resistance. As the temperature is lowered the resistance will decrease, first because $k_N^{-1}$ increases, thereby increasing $\Delta_N$ at a given point, and second because the electron energies decrease. Both effects tend to move the points of Andreev reflection away from the SN interfaces.

We have measured the resistances of two Pb-Ir-Pb sandwiches as a function of temperature, current density, and magnetic field. Iridium was chosen as the normal metal because it has a measurable transition temperature; it also forms no alloys with lead, and lead and iridium are almost completely mutually insoluble.[6] The Ir had a low temperature mean free path of approximately 200Å, and was in the dirty limit below 2K, at which temperature $k_N^{-1} \simeq 800$Å. A thin foil (~ 50μm) of the Ir was carefully cleaned, and a disk of Pb, of area 0.079 $cm^2$ and thickness about $10^{-3}$ cm, was evaporated on to each side. Electrical connection was made to the Pb disks by means of Pb pressure contacts. The samples were connected in series and mounted in a dilution refrigerator. The resistance of either sample, about $10^{-8}\Omega$, was measured with a superconducting voltmeter.[7] Outside the refrigerator were three mu-metal shields which reduced the ambient magnetic field to below $10^{-4}$G.[8]

The variation of resistance with temperature for the two Pb-Ir-Pb samples is shown in Fig. 1(c). The displacement of the curves is almost exactly accounted for by the difference in thickness of the Ir foils. At about 2K, the resistance was equal to the measured bulk resistance of the Ir, to within the absolute experimental accuracy (± 5%). The boundary resistance was therefore negligible. As the temperature was lowered, the resistance dropped markedly, becoming zero just above the transition temperature of the Ir,[9] which was measured independently to be 57mK. This fall-off in resistance we attribute to the Andreev scattering mechanism described above. The sharp increase in resistance near the transition temperature, $T_{cS}$, of Pb (7.2K) arises from propagation of electrons with energies greater than $\Delta_S^{(i)}$ from the N region into the superconductor, where they decay dissipatively.[10] The dip in resistance at 6K may be due to interference effects discussed by McMillan.[11] Both the dip and the sharp rise in resistance will be described in detail elsewhere.

We confine ourselves here to temperatures below 2K. Because the incident electrons have a distribution of energies, the conversion of normal current to supercurrent by Andreev reflection occurs over an extended region in N. In this region, there is an electric field necessary to maintain the quasiparticle current, and, in addition, a pair condensate that is carrying the supercurrent. The electrochemical potential difference gives rise to a time-dependence of the phase of this condensate, which most likely implies vortex motion. We do not yet have a theory which relates these processes to the resistance. However, the very simple model which follows gives a quite good fit to the observed temperature dependence of the resistance.

Consider one half of the SNS junction, the region $0 < x < a$ being Ir, and the region $x < 0$ being Pb. Suppose that all of the incident electrons have energy kT and are Andreev scattered at a point $x_o$ in the N region where $\Delta_N(x_o) = kT$. The total measured resistance R(T) of the junction is therefore just

$$R(T) = (a - x_o)R_o/a, \qquad (2)$$

where $R_o$ is the bulk resistance of the Ir slab. According to the de Gennes theory,[1] one boundary condition at the SN interface is $\Delta_N^{(i)}/(NV)_N = \Delta_S^{(i)}/(NV)_S$. In the normal region $0 < x < a$, the value of resistance is nearly independent of current.

In Fig. 3 we show the dependence of resistance upon a magnetic field applied in the plane of the sample. The magnetic field also quenches the superconductivity in the tails of the two decaying pair potentials. At 70mK and 90mK, the resistance is almost independent of current at high fields, suggesting that the quenching effect of the field dominates, while at low fields, the resistance is strongly current dependent, suggesting that the effect of the current dominates. Since the penetration depth is greater than $k_N^{-1}$ in part of N, there is a region in which we expect type II behavior. In fact, the shape of the curves at the lower two temperatures is very similar to the voltage vs magnetic field curves of a type II superconductor in the flux-flow regime.[12] At low fields, the vortices are pinned, and the resistance is not strongly affected by field. At roughly 0.5G, the vortices begin to move, and the resistance rises more rapidly with increasing field, until an equivalent of $H_{c2}$ is reached at about 5G.

It is clear that much remains to be done theoretically before a quantitative interpretation of our results can be made. In particular, it seems important to understand the time-dependence of the induced condensate. We are currently working on a more detailed phenomenological theory as well as making measurements with normal metals that are not known superconductors.

We are indebted to James Kruger for fruitful suggestions and assistance in running the dilution refrigerator, to Professor Marvin Cohen for many helpful discussions, and to Keith Kawate for help with specimen preparation.

# FIGURE CAPTIONS

Fig. 1(a). Variation of pair potential Δ across SN interface for $V_N = 0$. Incident electron is reflected at the SN interface. (b) Variation of pair potential Δ across SN interface for $V_N > 0$. Incident electron is reflected inside N. (c) Variation of resistance with temperature for two Pb-Ir-Pb samples. Thickness of Ir in 8C was 53 ± 1μ, and in 8D 54 ± 1μ. The theoretical curve is for 8C.

Fig. 2. Variation of resistance with current density for Pb-Ir-Pb sample 8C at different temperatures.

Fig. 3. Effect of magnetic field upon resistance for Pb-Ir-Pb sample 8C for various current densities at different temperatures.

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1. P. D. de Gennes, Rev. Mod. Phys. 36, 225 (1964).
2. J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).
3. A. F. Andreev, Zh. Eksperim. i Teor. Fiz. 46, 1823 (1964) [Sov. Phys. JETP 19, 1228 (1964)].
4. B. D. Josephson, Phys. Letters 1, 251 (1962).
5. J. Clarke, Proc. Roy. Soc. (London) A308, 447 (1969).
6. M. Hansen, Constitution of Binary Alloys (McGraw-Hill, New York, 1958, 2d Ed.).
7. J. Clarke, Phil. Mag. 13, 115 (1966).
8. S. M. Freake and T. L. Thorp, Rev. Sci. Instr. 42, 1411 (1971).
9. The low purity of the foil, 99.9%, probably accounts for the reduction in transition temperature from the accepted value of 0.14 K.
10. A. B. Pippard, F. R. S., J. G. Shepherd, and D. A. Tindall, Proc. Roy. Soc. (London) A324, 17 (1971).
11. W. L. McMillan, Phys. Rev. 175, 559 (1968).
12. See, for example, Y. B. Kim and M. J. Stephen in Superconductivity R. D. Parks, Ed. (Marcel Dekker, Inc., New York, 1969), p. 1117.

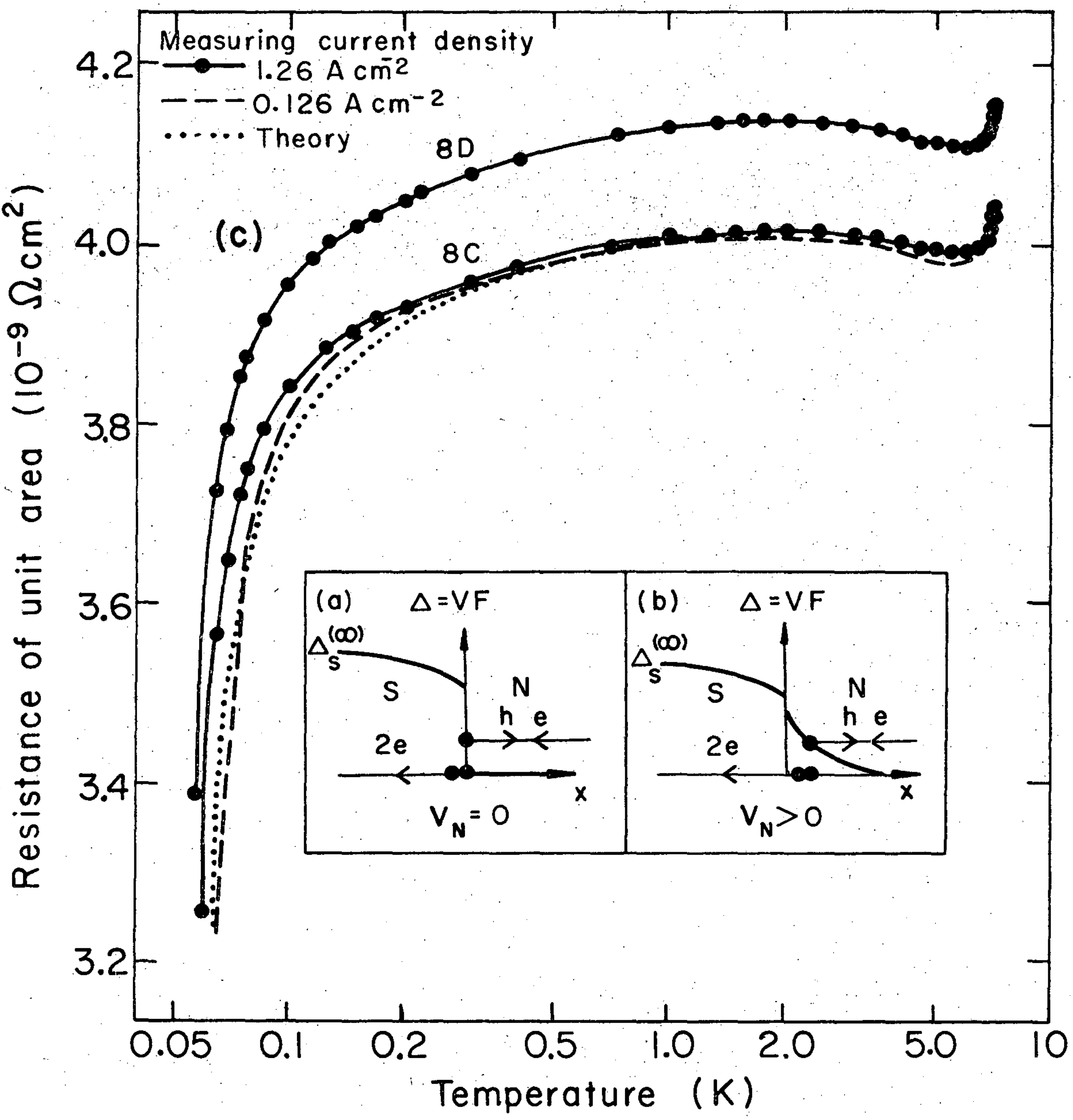

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Fig. 1

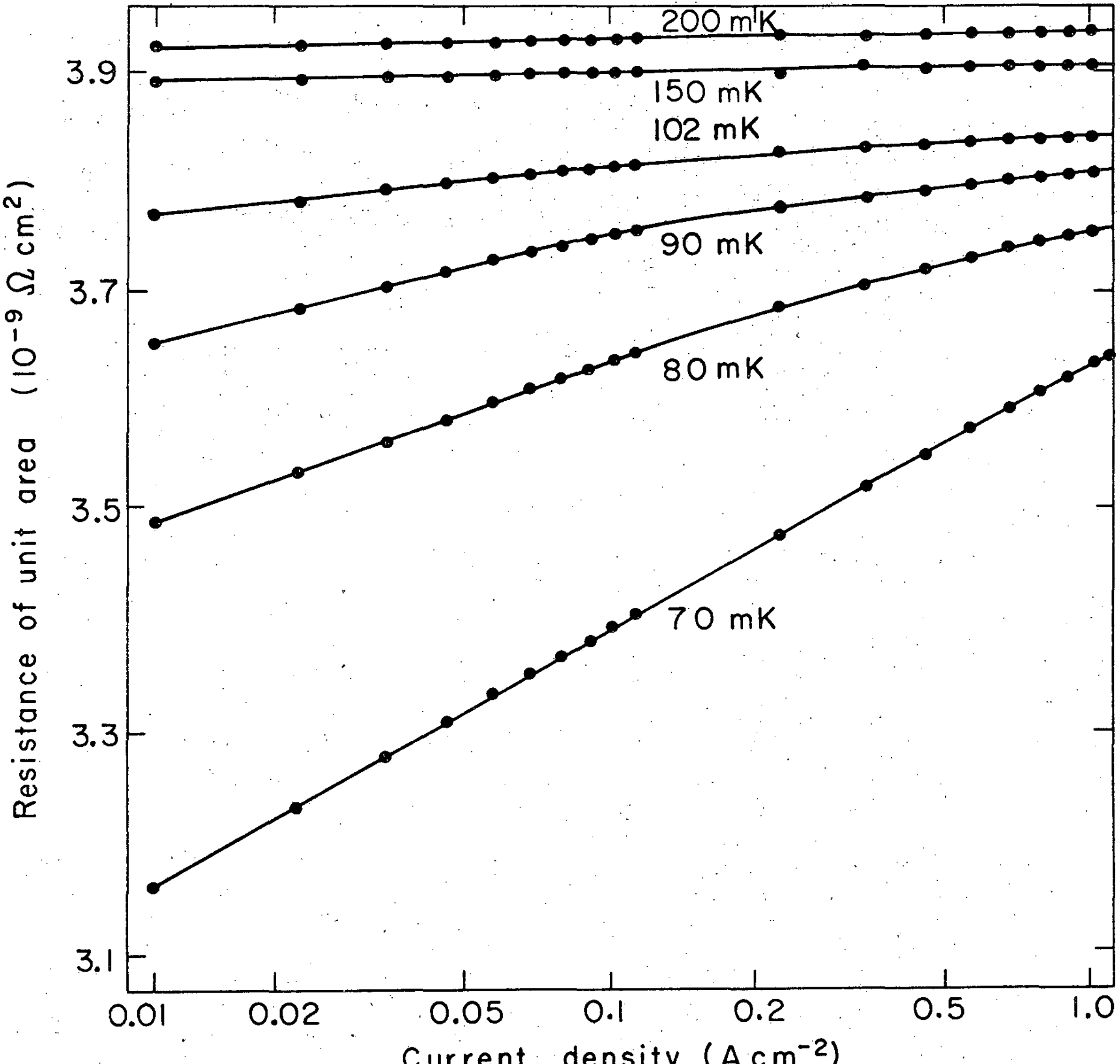

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Fig. 2

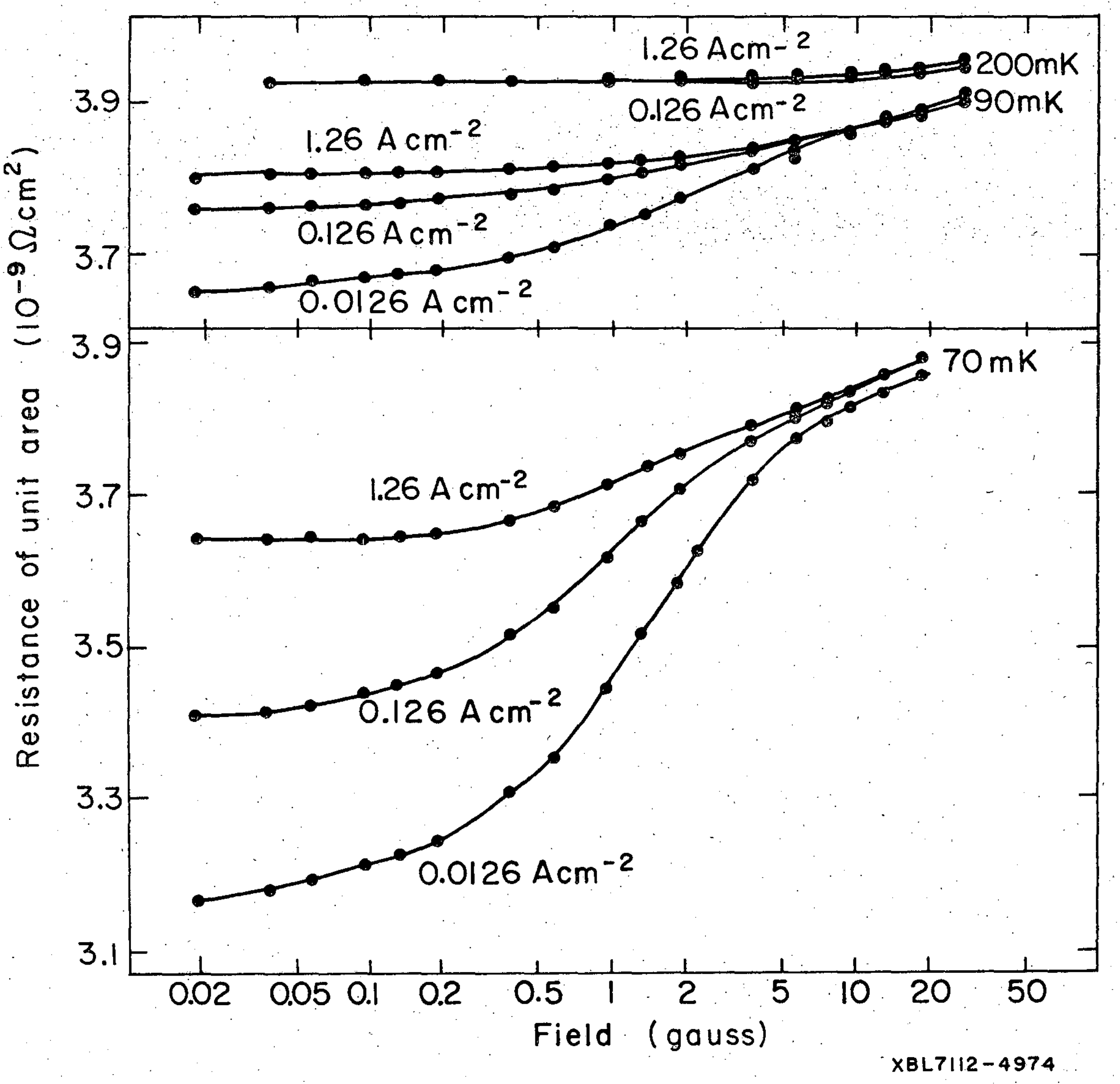
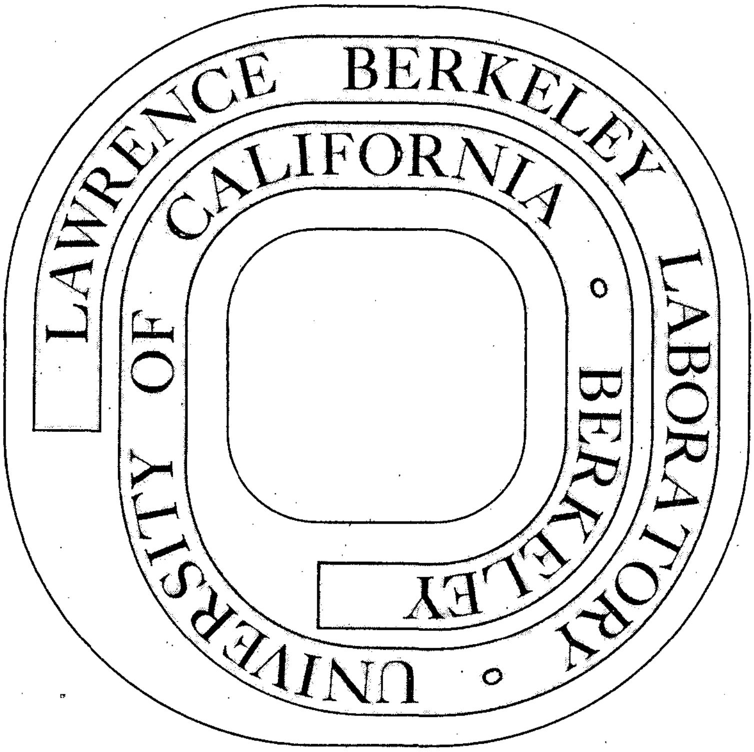

1.26 Acm⁻²
200mK
0.126 Acm⁻²
90mK
1.26 A cm⁻²
0.126 A cm⁻²
0.0126 A cm⁻²
70 mK
1.26 A cm⁻²
0.126 A cm⁻²
0.0126 Acm⁻²
3.9
3.7
3.9
3.7
3.5
3.3
3.1
Resistance of unit area (10⁻⁹ Ωcm²)
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
Field (gauss)
XBL7112-4974

Fig. 3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