a point-by-point measurement would be.

The method proposed here can also be used to determine the shape of the Fermi surface in semimetals and semiconductors. In fact, measurements of this effect in bismuth have already been made.[10] In these materials it is not always true that $\omega \ll \omega_c$, and the equations given here have to be modified accordingly. In particular, k_H in Eqs. (1′), (5′), and (7) has to be replaced by $k_H(1-\omega/\omega_c)^{-1}$. In these materials, because $\omega \approx \omega_c$, the same equipment that measures the properties of the helicons (ω and k_H) can also measure ω_c and thus determine the same geometric properties as for metals.

It has been pointed out to the author after this paper was written that the analysis presented here for helicons has already been done for the case of circularly polarized transverse sound waves.[11,12] The general ideas in the analysis for both helicons and circularly polarized sound waves propagating along a magnetic field are the same, but the details are somewhat different. However, helicons appear to be a much more useful means than circularly polarized sound waves to study this onset of the Doppler-shifted absorption. It is not possible to produce circularly polarized transverse sound waves except along a few high-symmetry directions.[11,12] Helicons do not have this limitation and can propagate in all directions. It also appears that the distinction between the onset of absorption at a point or at a finite-sized orbit is more striking for helicons.

In conclusion, a caution should be inserted. The derivation given here has assumed an independent-particle model for the electrons in the metal. If many-body effects are important they may invalidate the results given here.

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OBSERVATION OF PERSISTENT CURRENT IN A SUPERCONDUCTING SOLENOID

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The classical experiment of Onnes,[1] in which a persistent current is induced in a closed superconducting circuit and the trapped magnetic field observed over a period of time, has been repeated several times.[2-6] From the length of the period of observation and the accuracy of the measurement, one can set a lower limit to the time constant of the circuit. Apparently the highest value to this limit was set in the experiment of Collins[3] at a value of approximately 250 years.

To extend this limit by several orders of magnitude, we undertook to apply modern nuclear magnetic resonance (NMR) techniques to the measurement of the field. A double layered solenoid of 984 turns of 0.020-in. diameter Nb-25% Zr alloy approximately 4 in. in diameter and 10 in. long as shown in Fig. 1 was constructed to provide a homogeneous field. The measured axial field profile of the central 0.5 in. is shown in Fig. 2. The terminals of the coil are permanently connected by spot welding.

After inducing a persistent current in the coil, its magnetic field was measured by NMR techniques and recorded with time. The first run ex-

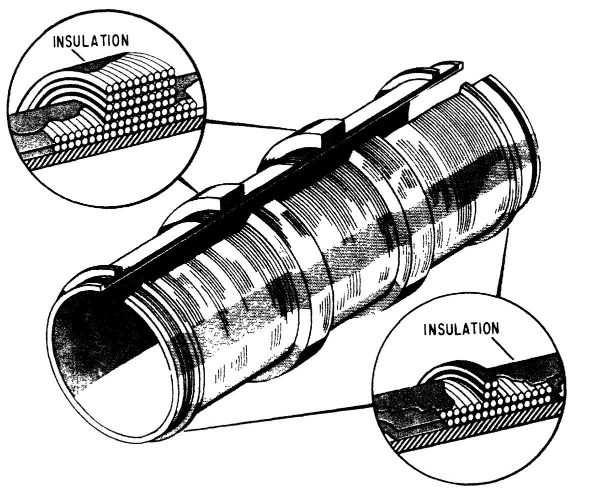

FIG. 1. Construction of solenoid.

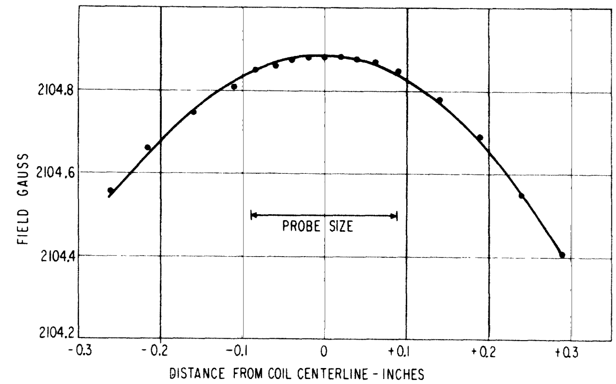

FIG. 2. Measured axial field profile.

tended over a period of 21 days, and was terminated at that time because of two coincidental accidents – one a failure in the electronic system, and the other a mechanical shock to the system which probably disturbed the position of some of the turns and the position of the probe. The supercurrent, however, was maintained, and the experiment continued. The observed data of run one seemed to indicate a real field decay. Since the probe had been displaced from the field maximum, it was not possible to determine the contribution to apparent decrease in field by this mechanical shift.

A slightly inferior set of electronics was substituted and the measuring technique changed to reposition the probe to field maximum before each measurement. This introduces more scatter in the data but eliminates the possibility of a positional shift indicating a false decrease.

Run two extended over a period of 37 days, beginning 9 days after the end of run one. The data are shown in Fig. 3. The solid lines are least-squares fits of the data to the leading terms of an exponential decay,

$$B = B_0(1 - t/\tau), \tag{1}$$

where B = observed field strength, B_0 = field strength at time zero, and τ = time constant of the circuit, giving the results shown in Table I. The result of run two is consistent with that of run one.

An attempt has been made to correlate the data with the work of Kim, Hempstead, and Strnad[7] based on the flux-creep theory of Anderson.[8] In their work, field decays were observed of the form

$$B = B_c - c\ln(t/t_c), \tag{2}$$

where B is the observed field as a function of time,

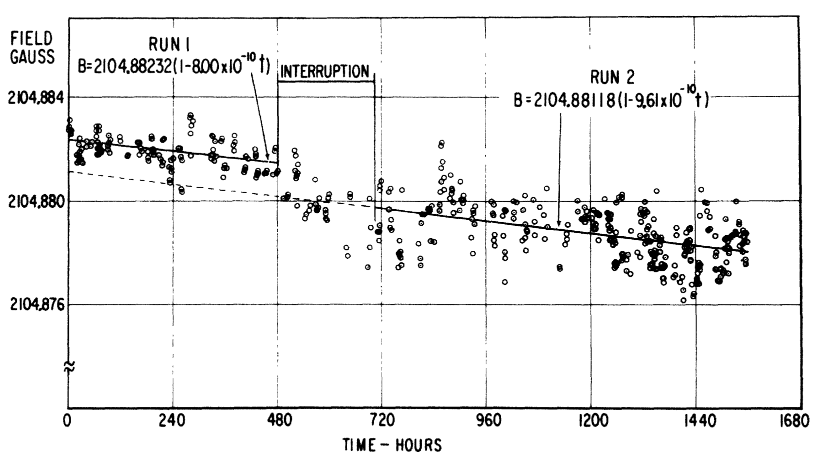

FIG. 3. Experimental data for runs one and two.

Table I. Results of least-squares fit.

	Run one	Run two
B_0 (gauss)	2104.88232 ± 0.000049	2104.88118 ± 0.000085
Observed slope (gauss/h)	$(1.684 \pm 0.19) \times 10^{-6}$	$(2.022 \pm 0.15) \times 10^{-6}$
Time constant (yr)	144 500 ± 16 300	119 450 ± 8700
Upper limit to the equivalent resistivity Nb-25% Zr wire (ohm-cm)	4.3×10^{-22}	4.9×10^{-22}
Maximum resistance of spot weld, assuming it to be entire resistance of circuit (ohm)	6.5×10^{-15}	7.4×10^{-15}

t, and the terms B_c, c, and t_c are constants.

The decay rates given, respectively, by the two expressions (1) and (2) are

$$dB/dt = -B_0/\tau \tag{3}$$

and

$$dB/dt = -(c/t_c)\exp[(B_c - B)/c]. \tag{4}$$

The runs one and two were made at approximately 600 gauss below critical field, which is too low to allow a comparison between relationships (1) and (2) in a relatively short period of time. Consequently, run three was undertaken at approximately 36 gauss below the critical field. The data for run three are shown in Fig. 4. Difficulty in attaining a field close to the critical field required the coil to be driven normal and re-energized some 50 times. The cycling caused the homogeneity of the field over the length of the sample to deteriorate by about an order of magnitude. This resulted in a wider scatter of the data and considerably less accurate measurement of the slope than in runs one or two. However, if the effect described by relationship (2) were the only decay mechanism operating, the slope would be so much greater at the higher field that the decay would be very apparent.

This follows from (4) by taking the ratio of slopes at two different field levels, B_1 and B_2:

$$\frac{dB_1/dt}{dB_2/dt} = \exp\left(\frac{B_2 - B_1}{c}\right). \tag{5}$$

Expression (2) may be rewritten as

$$B = B' - c\ln t, \tag{6}$$

where

$$B' = B_c + c\ln t_c$$

and

$$dB/dt = -c/t. \tag{7}$$

In this theory, B' is not uniquely defined, but it is reasonable to assume that B' is approximated

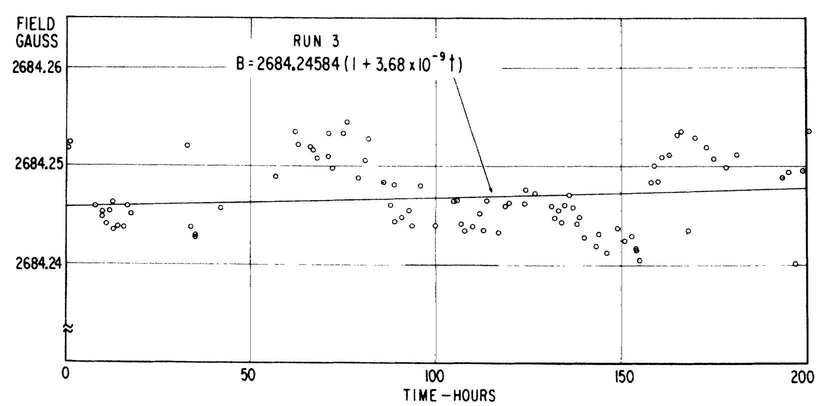

FIG. 4. Experimental data for run three.

by the highest field experimentally attainable, that is, a quantity very close to critical field. Having made this assumption, the constant c then can be evaluated from (6), (7), and the experimental results of run two. For an observed B' of 2720 gauss, c is calculated to be about 37 gauss per e-fold. Applying (5) to runs two and three, it is computed that the ratio of the decay rate of run three to that of run two should be 6.6×10^6, in which case the field as a function of time would be represented by a vertical line on Fig. 4.

It is quite clear that if flux creep is present in this experiment, it is masked by a stronger effect. Two possible explanations other than energy dissipation in the superconductor are these:

(a) The spot weld may have a finite resistance.

(b) The radial magnetic pressure of about 2.7 psi causes a tensile stress of 175 psi in the wire. If the wire is experiencing a mechanical creep, then an average increase of coil radius of only two microinches would explain the total field change of runs one and two.

All of the runs of this experiment were made in the superconducting portion of the critical state diagram, whereas the experiments of Kim, Hempstead, and Strnad were done just outside this region. The decay laws may be different on the two sides of the critical state curve.

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GAPLESS SUPERCONDUCTIVITY

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The possibility that a metal containing paramagnetic impurities could become superconducting without possessing a well-defined energy gap has been discussed[1] by Abrikosov and Gor'kov (AG). Recently two effects of paramagnetic impurities on the superconducting characteristics of thin In films have been studied.[2] These are the dc resistance, which gives the transition temperature T_s as a function of c, the atomic percent of magnetic impurities, and the $I-V$ tunneling characteristic. The result was found that Δ, the energy gap derived from the $I-V$ characteristic, appeared to decrease with c almost twice as fast as T_s. It disappeared ($I-V$ Ohmic) at $c=1\%$, although T_s was still nearly half the value in the pure metal.

Both the theoretical and experimental results just quoted appear to contradict the sum rule[3] which relates the supercurrent strength (i.e., the penetration depth in the London limit) to the difference in area $[\sigma_n(\omega)-\sigma_s(\omega)]/\omega$. The purpose of this note is to clarify the meaning of "energy gap" in a superconductor containing paramagnetic impurities. To do so we need not change any of AG's equations, but only their physical interpretation.

According to AG, at $T=0$ the Fourier components of the quasi-particle correlation function $G(\vec{p},\tilde{\omega})$ are given by

$$G(\vec{p},\tilde{\omega})=(\tilde{\omega}+\xi)/(\tilde{\omega}^2-\xi^2-\tilde{\Delta}^2). \qquad (1)$$

In the absence of impurity scattering the poles of (1) give the usual quasi-particle energies

$$\tilde{\omega}=\pm(\xi^2+\tilde{\Delta}^2)^{1/2}, \qquad (2)$$

where $\xi=v_0(p-p_0)$. In the presence of impurity scattering, $\tilde{\omega}$ and $\tilde{\Delta}$ are altered to

$$\tilde{\omega}=\omega+(1/2\tau_1)u/(1-u^2)^{1/2}, \qquad (3)$$

$$\tilde{\Delta}=\Delta+(1/2\tau_2)1/(1-u^2)^{1/2}, \qquad (4)$$

where ω is the (real) energy variable. Here u is an implicit function of ω defined by $u=\tilde{\omega}/\tilde{\Delta}$. The total scattering rate is $1/\tau_1$, and the spin-flip scattering rate is proportional to

$$1/\tau_s=1/2\tau_1-1/2\tau_2. \qquad (5)$$

From (3)-(5) one finds a consistency equation which determines the contribution of each state

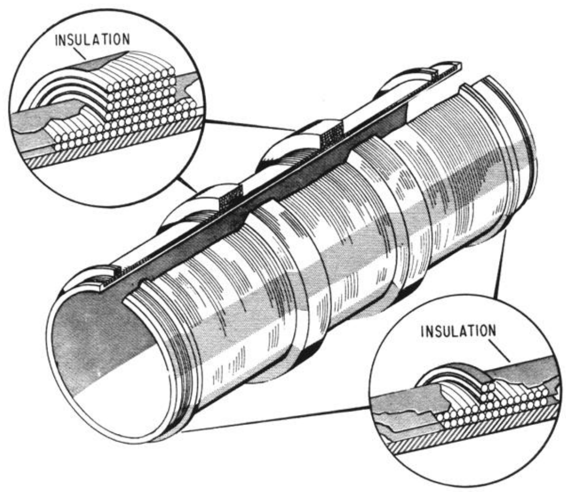

FIG. 1. Construction of solenoid.